Simon Lacey · Rebecca Lawson   *Editors*

Multisensory Imagery

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Editors
Simon Lacey
Department of Neurology
Emory University School of Medicine
Atlanta, Georgia, USA

Rebecca Lawson
School of Psychology
University of Liverpool
Liverpool, UK

Contents

Contributors

Helen A. Anema, Ph.D. Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, The Netherlands

Sonal Arora, B.Sc. M.B.B.S., M.R.C.S., Ph.D. Department of Surgery, Imperial College, London, UK

Paolo Bartolomeo, M.D., Ph.D. Inserm-UPMC UMRS 975, Brain and Spine Institute, Groupe Hospitalier Pitié-Salpêtrière, Paris, France

AP-HP, Groupe Hospitalier Pitié-Salpêtrière, Fédération de Neurologie, Paris, France

Department of Psychology, Catholic University, Milan, Italy

M. Bensafi, Ph.D. CNRS, UMR5292, Lyon Neuroscience Research Center, University Lyon, Lyon, France

Université Claude Bernard, Lyon, Garnier, Lyon, France

Olesya Blazhenkova, Ph.D. Department of Psychology, National University of Singapore, Singapore

Alexia Bourgeois, M.A. Department of Neuropsychology, Hôpital Pitié-Salpêtrière, Paris, France

Clémence Bourlon, Ph.D. Department of Neurology, Clinique Les Trois Soleils, Boissise le Roi, France

Zaira Cattaneo, Ph.D. Department of Psychology, University of Milano-Bicocca, Milan, Italy

Brain Connectivity Center, IRCCS Fondazione Mondino Pavia, Italy

Cesare Cornoldi, Ph.D. Department of General Psychology, University of Padova, Padova, Italy

Catherine Craver-Lemley, Ph.D. Department of Psychology, Elizabethtown College, Elizabethtown, PA, USA

Ophelia Deroy, Ph.D. Center for the Study of the Senses, Institute of Philosophy, University of London, London, UK

H. Chris Dijkerman, D.Phil. Experimental Psychology, Helmholtz Institute, Utrecht University, Utrecht, The Netherlands

Department of Neurology, University Medical Centre Utrecht, Utrecht, The Netherlands

Alberto Gallace, Ph.D. Department of Psychology, University of Milano-Bicocca, Milan, Italy

Giorgio Ganis, Ph.D. School of Psychology, Cognition Institute, University of Plymouth, Plymouth, UK

Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, MA, USA

Department of Radiology, Harvard Medical School, Boston, MA, USA

Nicholas A. Giudice, Ph.D. Spatial Informatics Program: School of Computing and Information Science, University of Maine, Orono, ME, USA

Emily A. Holmes, D.Clin.Psy., Ph.D. MRC Cognition and Brain Sciences Unit, Cambridge

Timothy L. Hubbard, Ph.D. Department of Psychology, Texas Christian University, Fort Worth, TX, USA

Eva Kemps, Ph.D. School of Psychology, Flinders University, Adelaide, SA, Australia

Roberta L. Klatzky, Ph.D. Department of Psychology, Carnegie-Mellon University, Pittsburgh, PA, USA

Maria Kozhevnikov, Ph.D. Department of Radiology, Harvard Medical School, Martinos Center for Biomedical Imaging, Charlestown, MA, USA

Department of Psychology, National University of Singapore, Singapore

Julie Krans, Ph.D. School of Psychology, University of New South Wales, Kensington Campus, NSW, Australia

Simon Lacey, Ph.D. Department of Neurology, Emory University School of Medicine, Atlanta, GA, USA

Rebecca Lawson, Ph.D. School of Psychology, University of Liverpool, Liverpool, UK

Jack M. Loomis, Ph.D. Department of Psychological and Brain Sciences, University of California, Santa Barbara, Santa Barbara, CA, USA

Britta Lorey, Dipl. Psych., Ph.D. Neuromotor Behavior Lab and Bender Institute for Neuroimaging, Institute for Sport Science, Justus Liebig University Giessen, Giessen, Germany

Francine Malouin, Ph.D. Department of Rehabilitation, Faculty of Medicine, Laval University, Quebec City, QC, Canada

Center for Interdisciplinary Research in Rehabilitation and Social Integration (CIRRIS), Quebec City, QC, Canada

Raffaella Migliaccio, M.D., Ph.D. Inserm-UPMC UMRS 975, Brain and Spine Institute, Hôpital Pitié-Salpêtrière, Paris, France

Department of Psychology, Catholic University, Milan, Italy

Aidan Moran, B.A., M.A., Ph.D., F.B.Ps.S.I., A.F.B.Ps., C. School of Psychology, University College Dublin, Dublin, Ireland

Jörn Munzert, Ph.D. Neuromotor Behavior Lab and Bender Institute for Neuroimaging, Institute for Sport Science, Justus Liebig University Giessen, Giessen, Germany

Roger M.K. Ng, M.R.C.Psych., F.H.K.A.M. Department of Psychiatry, Kowloon Hospital, Kowloon, Hong Kong, China

J. Poncelet, Ph.D. CNRS, UMR5292, Lyon Neuroscience Research Center, University Lyon, Lyon, France

L. Przybylski, M.Sc. CNRS, UMR5292, Lyon Neuroscience Research Center, University Lyon, Lyon, France

Adam Reeves, Ph.D. Department of Psychology, Northeastern University, Boston, MA, USA

Chiara Renzi, Ph.D. Department of Brain and Behavioral Sciences, University of Pavia, Pavia, Italy

Carol L. Richards, O.C., Ph.D. Department of Rehabilitation, Center for Interdisciplinary Research in Rehabilitation and Social Integration, Quebec, QC, Canada

C. Rouby, Ph.D. CNRS, UMR5292, Lyon Neuroscience Research Center, University Lyon, Lyon, France

K. Sathian, M.D., Ph.D. Department of Neurology, Emory University School of Medicine, Atlanta, GA, USA

Department of Rehabilitation Medicine, Emory University, Atlanta, GA, USA

Department of Psychology, Emory University, Atlanta, GA, USA

Rehabilitation R&D Center of Excellence, Atlanta VA Medical Center, Decatur, GA, USA

Haline E. Schendan, Ph.D. School of Psychology, Cognition Institute, University of Plymouth, Drake Circus, Plymouth, Devon, UK

Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Charlestown, MA, USA

Nick Sevdalis, B.Sc., M.Sc., Ph.D. Department of Surgery and Cancer, St. Mary's Hospital, London, UK

Charles Spence, Ph.D. Crossmodal Research Laboratory, Department of Experimental Psychology, University of Oxford, Oxford, UK

Marika Tiggemann, Ph.D. School of Psychology, Flinders University, Adelaide, SA, Australia

B. Tillmann, Ph.D. CNRS, UMR5292, Lyon Neuroscience Research Center, University Lyon, Lyon, France

Tomaso Vecchi, Ph.D. Department of Brain and Behavioral Sciences, University of Pavia, Pavia, Italy

Brain Connectivity Center, IRCCS Fondazione Mondino, Pavia, Italy

Chapter 1
Introduction

Simon Lacey and Rebecca Lawson

Keywords Imagery • Unisensory • Multisensory • Crossmodal • Applied imagery
• Rehabilitation

1.1 There Is More to Imagery than the Mind's Eye

Are a beagle's ears bigger than a bulldog's? Which of Mona Lisa's hands is crossed over the other? We might answer such questions by engaging in visual imagery, using a mental representation that is similar to the visual representation that is activated when we really see a physical dog or a painting. Such quasi-perceptual visual experiences are often described as "seeing with the mind's eye." While such mental representations are being maintained, they can be inspected in order to determine that the beagle's ears are bigger and Mona Lisa's right hand is crossed over the left. But imagery is not restricted to vision: deciding whether the Moonlight Sonata would sound better if Brendel played it a little faster or whether a pear tastes sweeter than a peach appeals to imagery in other senses.

However, the visual sense has dominated for mental imagery as for many other fields, from the psychology of memory (Gallace and Spence 2009) to the study of

S. Lacey (✉)
Department of Neurology, Emory University School of Medicine,
WMB 6000, 101 Woodruff Circle, Atlanta, GA 30322, USA
e-mail: slacey@emory.edu

R. Lawson
School of Psychology, University of Liverpool,
Liverpool, UK

the senses in Renaissance literature (Cahill 2009). While there are several books devoted to visual imagery (e.g., Kosslyn 1980, 1994; Kosslyn et al. 2006; Richardson 1999), the other senses are less well represented (but see Reisberg (1992) for auditory imagery and Guillot and Collet (2010) for motor imagery). They are usually subsumed within a wider topic (e.g., musical but not other kinds of auditory imagery in Peretz and Zatorre (2003)) or are given only a cursory mention (e.g., Richardson 1999). Much the same can be said of applied imagery research where—although the visual sense does not dominate to the same extent—the nonvisual senses are still poorly represented (but see Mellalieu and Hanton (2009) and Van Raalte and Brewer (1996) for imagery in sports and exercise psychology and Guillot and Collet (2010) for motor imagery mainly in stroke rehabilitation).

Nevertheless, the last two decades have seen a huge increase in research into all aspects of multisensory processing (Foxe and Molholm 2009; Meyer and Noppeney 2011), evidenced by the establishment of a dedicated conference (the International Multisensory Research Forum), several general reference works (Calvert et al. 2004; Murray and Wallace 2012; Stein 2012), and some specialist volumes, for example, on crossmodal attention (Spence and Driver 2004) and multisensory object perception (Naumer and Kaiser 2010). This being the case, we felt it was time that a single volume surveyed what we currently know about imagery in this wider sensory context. Note that we use the term "multisensory imagery" in its wider, nontechnical meaning (see Stein et al. 2010, for a discussion of more technical definitions and a proposal for a common terminology in the multisensory field) and aim to provide an overview of unisensory imagery in all the senses and the extent to which imagery in one modality may influence imagery or perception in another modality. We also review how imagery from different modalities could be used in an applied setting.

1.2   A Brief Historical Background to Our Understanding of the Role of Imagery

The idea of mental images and, especially, visual images as a vehicle for thought has its first recorded roots in the Platonic dialog *Theaetetus* (Plato 1987) and Aristotle's *De Anima* (Aristotle 1986). The scientific investigation of imagery began in the late nineteenth century with Francis Galton (Burbridge 1994). Early investigations relied heavily on introspection, with participants simply reporting on their conscious experience of carrying out a specified task. However, it soon became clear that people often had no conscious experience of how they performed a task or that their experience could not be described accurately or did not involve imagery (for modern examples, see Nisbett and Wilson 1977; Johansson et al. 2005).

The "imageless-thought controversy" that ensued (see Kroker 2003) resulted in the rejection of introspection in favor of investigating observable and measurable events. In America, this took the form of a radical behaviorist movement and mental

imagery became an object of scorn—"sheer bunk" as Watson (1928, p 77) put it. But during the "cognitive revolution" that followed the demise of behaviorism, visual imagery once again became a topic of legitimate interest. An iconic study by Shepard and Metzler (1971) showed that the time taken to decide whether two visually presented objects had the same shape increased linearly with the angular disparity between them, while Kosslyn (1973) demonstrated that the time to verify a property of an imaged object increased with the distance of the property from the imagined starting point. These influential experiments suggested that images preserved spatial properties of the stimulus and that different imagery processes, such as mental rotation and scanning, could operate on images. This research culminated in a detailed model of visual imagery (Kosslyn 1980, 1994; Kosslyn et al. 2006).

Despite these advances, imagery research remained contentious for much of this time. It came under particularly intense scrutiny during the "imagery debates" (Kosslyn 1994; Kosslyn et al. 2006; Pylyshyn 2002, 2003) over whether mental representations could include images (analogical, depictive representations) or consisted only of propositions (language-like descriptions). The difference between analogical and propositional representations is shown by an example from Kosslyn et al. (2006): take the pattern A and a verbal description of it as "two diagonal lines that meet at the top, joined halfway down by a short horizontal segment" (p 12). These both represent the same thing, but they differ in the ease of access to different types of information. For example, it is much easier to decide that there is an enclosed space and to determine its shape from inspecting the pattern than from reading the description. The pattern is like a picture in that it resembles the thing that it represents. The description is a propositional representation which is like a sentence that specifies a state of affairs.

Detailed accounts of the imagery debates can be found in Tye (1991), Kosslyn (1980, 1994), Kosslyn et al. (2006), and Pylyshyn (2002, 2003). Here we provide a brief summary of some of the main issues. First, results from imagery studies may simply reflect participants detecting, perhaps unconsciously, clues as to the expected outcome of the study (Orne 1962). However, although experimenter expectancies could be induced in imagery experiments and did affect outcomes (Intons-Peterson 1983), the critical imagery result, that of a linear increase in response time with distance to be scanned, was still found. It also survived even when different experimenters were told to expect either a linear increase, a linear decrease, or a U-shaped, nonlinear function (Jolicoeur and Kosslyn 1985). In addition, it is found when the instructions do not contain any reference to scanning, rotating, or even generating an image (e.g., Shepard and Metzler 1971). Thus, although expectancies and demand characteristics are potential pitfalls, as in many areas of psychology, it is unlikely that they account for all imagery findings and careful experimental design should avoid most such problems.

Second, participants in imagery experiments may interpret the task instructions by reference to their tacit knowledge of the properties of physical space and visual perception (Pylyshyn 1981). For example, if asked to scan across or rotate an image, participants may assume that they are to behave as though they were actually seeing an object. Here, longer response times may reflect their

knowledge that it takes longer to scan across longer distances in the physical world, rather than actual image processing. But Pylyshyn (2002) also claims that it is not always possible to determine what tacit knowledge people have, either by asking them or by testing their knowledge of psychology. However, unless one can determine what tacit knowledge people have, it would seem difficult to evaluate the claim that the results of imagery experiments reflect such knowledge. Also it seems unlikely that tacit knowledge could affect early neural mechanisms in order to account for neuroimaging studies that have shown, for example, that visual imagery typically activates retinotopic cortical areas (Kosslyn et al. 2002).

Third, Anderson (1978) pointed out that one can always provide a propositional explanation for depictive results and vice versa by trading structure against process. Take, for example, Shepard and Metzler's (1971) classic finding that the time to judge whether two objects have the same shape increases linearly with the angle that one has been rotated from the other. On a depictive account, there is a structure (a visual image of the object) and a process (mental rotation of the image). The further one has to rotate the image in order to bring it into alignment and make a judgment, the longer the response time. But on a propositional account, there could be a different structure (an ordered list of propositions corresponding to different rotations) and a different process (an ordered search through the list for a match). Here, larger rotations are further down the list and so the search takes a longer time. Thus, the same data can be explained by using different combinations of structures and processes. Anderson (1978) proposed that one way forward from this seeming impasse was to specify structure and process using nonbehavioral evidence and that an obvious starting point was what we know about the brain. For example, if a theory suggests that visual imagery employs many of the same processes as visual perception, then this account predicts that cortical areas involved in visual perception should also be involved in visual imagery (Kosslyn 1994). In contrast, an implicit assumption in propositional accounts is that imagery should use the brain regions involved in higher-order cognition rather than those involved in perception. A number of studies have now shown that visual imagery and visual perception engage many common brain areas (Kosslyn 1994; Kosslyn et al. 2006) and that the same is true for other modalities (see, e.g., Chaps. 5 and 6). It is difficult to see how a propositional approach can accommodate these findings.

Despite its sometimes contentious past, imagery research today is in rude health. One of the benefits of the intense and detailed arguments in the last century was that they pushed imagery researchers to clearly define their models, to improve their behavioral measures, and to seek converging evidence. Like many other fields, imagery has benefited from the ongoing revolution in neuroimaging techniques, including positron emission tomography, functional magnetic resonance imaging, and transcranial magnetic stimulation (see Chap. 15). These new methods have supported rigorous testing of a detailed model of visual imagery which is mapped onto a model of visual perception (Kosslyn 1994). To date, this has largely benefited our understanding of visual imagery, but developing and testing equally sophisticated models of imagery in other senses should be easier

given the example of visual imagery research in thrashing out such theoretical and methodological issues.

1.3 Organization of the Book

Skinner (1977, p 6) famously wrote, "There is no evidence of the construction of mental images to be looked at or maps to be followed. The body responds to the world at the point of contact; making copies would be a waste of time." The chapters in the first half of this book can be seen as providing theoretical arguments and empirical evidence to refute the first of these two claims, while those in the second half refute the second, focusing on the potential for providing practical applications based on our understanding of multisensory imagery.

1.3.1 Theoretical Perspectives

The first set of chapters reviews unisensory imagery in the five sensory modalities and motor imagery. Ganis (Chap. 2) discusses the shared neural basis for visual imagery and perception and reviews evidence for imagery-related activity from early visual cortex in V1 to later areas in the ventral visual stream. In Chap. 3, Gallace reviews the evidence for somesthetic imagery, suggesting ways in which the rather limited evidence base for tactile and haptic imagery could be expanded and how the field could be extended to, for example, imagery of pain. Hubbard (Chap. 4) assesses whether auditory imagery preserves some structural properties of auditory objects, such as pitch distance and musical contour, as well as the evidence for a shared neural substrate for auditory imagery and perception. Bensafi and colleagues review olfactory and gustatory imagery in Chap. 5. Like visual and auditory imagery, there is evidence for a common neural basis for olfactory imagery and perception, but the position is less clear for gustatory imagery. Finally, Anema and Dijkerman (Chap. 6) discuss motor and kinesthetic imagery where the shared neural substrate is common to imagery and execution, rather than imagery and perception.

We continue with two chapters covering spatial imagery. Renzi and colleagues (Chap. 7) deal with the nature of spatial imagery in the blind. In Chap. 8, Loomis, Klatzky, and Giudice assess whether spatial images derived from language or from multiple modalities exhibit functional equivalence; that is to say, the extent to which behavior requiring spatial imagery is the same irrespective of how input information was presented for encoding.

Later chapters review how imagery in the different senses interacts and how perception in one modality may be influenced, or may involve, imagery in another modality and vice versa. Spence and Deroy (Chap. 9) discuss different situations which might involve crossmodal imagery, that is, when an image in one modality is triggered by perception or imagery in another modality and whether crossmodal

imagery might result from crossmodal perceptual completion. Synesthesia is often referred to as a kind of imagery, and in Chap. 10, Craver-Lemley and Reeves assess the evidence for this assumption. Two possible criteria for distinguishing imagery and synesthesia are the extent to which they are under voluntary control and whether they provide information about the world that is functionally useful. Lacey and Sathian (Chap. 11) discuss the concept of the "meta-modal" brain with a multisensory, task-based organization. They review studies showing activation of visual cortex during haptic shape perception and the evidence that this reflects concurrent visual imagery of the felt object. In Chap. 12, Hubbard discusses multisensory and crossmodal aspects of auditory imagery including connections to kinesthetics.

We conclude with three more methodological chapters. Bartolomeo and colleagues (Chap. 13) use data from brain-damaged patients to assess whether primary cortical areas are necessary to support visual and motor imagery. They argue that visual imagery need not rely on these areas whereas motor imagery does, providing an interesting counterpart to Chap. 2. Lacey and Lawson (Chap. 14) review the usefulness of vividness ratings as an index of imagery ability. We argue that theory-driven questionnaires are more useful and make suggestions for developing new questionnaires. Finally, in Chap. 15, Ganis and Schendan discuss the strengths and weaknesses of different methodological approaches: behavioral, neuroimaging, electrophysiological, and brain stimulation. The latter three techniques may help to provide objective insights into the private process of imagery; in particular, brain stimulation techniques such as transcranial magnetic stimulation have the potential to inform us about causal mechanisms.

1.3.2 Applied Perspectives

In the second half of the book, we aim to show how imagery may be used to provide substantial practical benefits, whether for honing expert skills (in the initial three chapters) or in therapeutic or rehabilitation settings (in the following three chapters).

The first three chapters discuss the use of imagery in skilled performance. Kozhevnikov and Blazhenkova (Chap. 16) assess how visual object and spatial imagery and individual preferences for using different kinds of visual imagery are linked to academic performance and professional specialisms. Suggestions are made to develop educational strategies that play to individual strengths in a specific type of imagery as opposed to having a "one-size-fits-all" approach that treats imagery as an undifferentiated ability. In Chap. 17, Munzert and Lorey review how motor and visual imagery can enhance sporting performance across a range of skill levels. They provide evidence that mental rehearsal of future actions can improve performance and that imagery strategies may also reduce stress and aid rehabilitation after injury. Finally, in Chap. 18, Sevdalis, Moran, and Arora discuss imagery in medical surgery. Surgical trainees have traditionally learned "on the job," under the supervision of expert surgeons. Research in this area is in its infancy, but there is

now some evidence that mental practice can improve surgical performance and that expert surgeons may spontaneously develop such strategies.

Chapters 19 and 20 consider what might be termed the "dark side" of imagery: intrusive and unwanted imagery which may be disturbing and maladaptive. Ng, Krans, and Holmes (Chap. 19) show that such imagery is a feature in many psychological disorders. In particular, they concentrate on post-traumatic stress disorder (PTSD) and bipolar disorder. In Chap. 20, Kemps and Tiggemann discuss the role of intrusive imagery in various modalities in the experience of cravings. They review imagery in the context of cravings for alcohol, food, and activities such as gambling. Both of these chapters assess how imagery may also be used as therapy. Lastly, Malouin and Richards (Chap. 21) review how motor imagery and mental practice can be used as rehabilitation interventions in stroke, Parkinson's disease, and phantom limb pain. In the final chapter, we summarize the main themes emerging from the contributions to this book and highlight some fruitful areas for further developments in multisensory imagery in theoretical and applied fields.

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Chapter 2
Visual Mental Imagery

Giorgio Ganis

Abstract Visual mental imagery is an important aspect of our mental life. Without it, we would be unable to reactivate and transform visual representations of objects and events that are not unfolding in front of us. Until recently, the investigation of visual mental imagery relied on subjective and behavioral paradigms. These paradigms typically only enabled us to examine the end product of visual mental imagery processes, making it impossible to resolve empirical questions such as which representations are shared by visual perception and imagery. This chapter illustrates how the conceptual and methodological frameworks introduced by cognitive neuroscience in the last three decades have enabled researchers to address these kinds of questions by leveraging our knowledge about the neuroscience of the primate visual system.

Keywords Cognitive neuroscience • Visual mental imagery • Visual perception • Top-down • Bottom-up • Striate cortex • Extrastriate cortex • Prefrontal cortex

2.1 Background

During most of our waking life, our visual systems extract information from the visual world to ensure smooth interactions with the environment. This is possible because, during perception, our brains construct and maintain internal representations of objects and events unfolding in the visual world. However, these internal

G. Ganis (✉)
School of Psychology, University of Plymouth,
Drake Circus, Plymouth, Devon, PL4 8AA, UK

Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital,
Charlestown, MA 02129, USA

Department of Radiology, Harvard Medical School, Boston, MA 02115, USA
e-mail: ganis@nmr.mgh.harvard.edu

representations can also be reactivated during visual mental imagery without the aid of any external visual stimuli, such as when we find ourselves visualizing people's faces from last weekend's party to figure out if a certain acquaintance was present or not. Mental imagery can take place in all modalities (visual, auditory, olfactory, and so on), but here the focus will be on visual mental imagery of shapes, probably the most well-studied modality and type of mental imagery.

To answer questions about the visual appearance of an object that is not in front of our eyes, such as "What shape is a pelican's beak?", one typically visualizes a pelican and then "zooms in" on parts of the image containing the animal's beak to assess its shape. Reactivating and inspecting internal representations in the absence of a corresponding external stimulus is one of the core aspects of mental imagery. Using the language of cognitive science, visual mental imagery involves reactivating visual representations in long-term memory and using them to construct representations in working memory; these representation can then undergo further processing, for example, by reinterpreting or transforming them (Kosslyn et al. 2001, 2006).

Although we have talked about reactivating internal representations, visual mental imagery entails more than the simple reactivation of visual representations of previously experienced events: People not only construct images using fragmentary information stored in long-term memory, but in many cases, they also can use visual mental imagery to extract new information (i.e., information that had not been encoded explicitly) by parsing and reassembling visual images in new ways (Finke et al. 1989). This constructive and combinatorial aspect of visual mental imagery is why it plays a key role in numerous domains, such as engineering and mathematics, and is important for numerous cognitive skills, such as reasoning (e.g., Blajenkova et al. 2006).

2.2   Visual Mental Imagery and Cognitive Neuroscience

Two general classes of theories have been put forward to account for the details of the internal organization of visual mental images. Depictive theories embrace the view that visual mental images are distinct types of mental representations and function to depict visual objects and scenes (Kosslyn 1980; Shepard and Cooper 1982). Under this view, visual images make explicit shape and spatial relations by virtue of their internal structure: Distances among parts in the image correspond to distances among parts of the stimulus they represent. In contrast, non-depictive theories support the view that visual mental image representations are not different from the type of "propositional" representations used for general-purpose thought (Pylyshyn 1981). According to this view, the pictorial aspects of imagery available to introspection are epiphenomenal and play no role in information processing. During the "imagery debate" of the late 1970s and early 1980s, behavioral evidence was found both in favor and against both theories. As the debate unfolded, it became more and more clear that these questions about internal representations could not be answered conclusively, even with the novel empirical methods of cognitive psychology. A clever theoretical paper (Anderson 1978) demonstrated formally that behavioral results from a class of visual imagery paradigms could be interpreted both

within a depictive and a propositional account of visual imagery simply by modifying the processing assumptions. Anderson showed that, for any theory defined by a set of assumptions about depictive representations and processes operating on them, it was possible to generate a second theory defined by an alternative set of assumptions about propositional representations and processes that could mimic the first theory. This finding illustrated that behavioral results alone were not strong enough to support conclusive inferences about specific representation–process pairs: Such inferences could only be made by using additional findings, such as those provided by neuroscientific research. This is one of the main reasons why evidence from neuroscience is crucial to constraining and understanding the details of how visual mental imagery works.

Behavioral studies showing parallels between visual mental imagery and perception provided an obvious starting point for using neuroscientific data (Kosslyn 1980). The logic here is that if visual mental imagery recruits the same processes engaged by visual perception, then the neural structures that support vision should also support visual mental imagery (Kosslyn 1994). Using this logic, one could leverage the large body of preexisting neuroscientific knowledge about the visual system of nonhuman animals to understand visual mental imagery. Until recently, information about the neurophysiological organization of the human visual system was mostly indirect and came from studies in nonhuman primates, under the assumption of homology among different species. Recent advances in noninvasive neuroimaging and brain stimulation techniques and paradigms have made it possible to test this assumption directly by enabling cognitive neuroscientists to study the neural basis of vision in humans. Cognitive neuroscience techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and transcranial magnetic stimulation (TMS) have provided evidence complementary to more traditional observations in brain-damaged patients and confirmed that the organization of the visual system in human and nonhuman primates, especially that of early visual areas, is quite similar (e.g., Sereno and Tootell 2005). These same techniques have also enabled the study of visual mental imagery noninvasively in humans.

In the following sections, we will review and discuss some of the classic and recent empirical literature on the cognitive neuroscience of visual mental imagery, focusing on the topic of the extent to which visual mental imagery and visual perception recruit similar neural resources.

2.3   Shared Neural Systems in Visual Mental Imagery and Perception

Do visual mental imagery and perception recruit similar brain regions and neural processes, as many cognitive studies have suggested? The handful of neuroimaging studies that have quantified the similarity between visual mental imagery and perception across the entire brain have found that there is substantial overlap (more than 90%) between brain regions recruited by visual perception and visual mental imagery

(e.g., Ganis et al. 2004). The vast majority of the neuroimaging literature, however, has focused on the qualitative question of whether, and under what circumstances, visual mental imagery recruits visual areas also recruited during visual perception. Next, we will review and discuss the results of some of these studies.

2.4 The Role of Early Visual Cortex in Visual Mental Imagery

Numerous studies have focused on the specific issue of whether visual mental imagery recruits early visual cortical areas engaged during visual perception. To understand why this question is key, it is necessary to review some basic principles of the organization of the primate visual system and to consider how these principles may relate to depictive theories of visual mental imagery.

The primate visual system is organized as a loose hierarchy of parallel processing streams (Felleman and Van Essen 1991), with early visual areas (areas V1 and V2, also known as areas 17 and 18, respectively) at the lowest level in the hierarchy. Area V1, in particular, is the first cortical region that receives visual information from subcortical nuclei (mostly from the lateral geniculate nucleus), which in turn receive input from the retina. V1 and V2 feed information to two parallel streams in the hierarchy, the ventral stream, which encompasses ventrolateral areas in the occipital and temporal lobes, and the dorsal stream, which encompasses dorsal areas in the occipital and parietal lobes (Desimone and Ungerleider 1989). These two streams have been implicated in two different sets of functions: The ventral stream subserves predominantly object vision (Desimone and Ungerleider 1989; Haxby et al. 1991; Mishkin et al. 1983; Ungerleider and Mishkin 1982), whereas the dorsal stream subserves primarily spatial vision and action (Goodale et al. 2004; Ungerleider and Mishkin 1982).

A defining attribute of early visual cortical areas is that they have a topographic organization in which nearby points in the visual space (which is projected onto the retina) are mapped onto nearby points on the cortical mantle. Thus, topographically organized areas employ distance on the cortex to represent distance in the visual space. This retinotopic representation of the visual space is defined by two dimensions in polar coordinates, eccentricity and polar angle. The eccentricity of a point is its distance from the fovea (the central, high-resolution, region of the visual field), whereas the polar angle is the angle between a line connecting the point to the center of the visual field and a horizontal line. Polar angle and eccentricity are represented in V1 along roughly orthogonal directions. As one ascends the visual hierarchy, this retinotopic organization becomes less and less precise (Felleman and Van Essen 1991; Fox et al. 1986; Heeger 1999; Sereno et al. 1995; Tootell et al. 1998). The receptive fields, that is, the region of the visual field "seen" by a neuron, are very small in area V1 and become larger and larger as one moves toward inferotemporal cortex. At the same time, the visual attributes to which neurons are selective become more and more complex in later visual areas. Neurons in area V1 are maximally driven by small bars at very specific spatial locations, but neurons in inferotemporal

cortex are maximally driven by specific combinations of shape, texture, and color appearing almost anywhere in the visual field (Fujita et al. 1992; Lehky et al. 2011; Miyashita and Chang 1988; Tanaka 1996; Tanaka et al. 1991). Because of this organization, the topographic code used in area V1 makes explicit the spatial layout of a stimulus, whereas the distributed code used in inferotemporal cortex makes explicit similarities between complex features of object classes (Lehky et al. 2011; Tanaka 1996).

Another key feature of the organization of the primate visual system is that visual areas that are connected via feedforward fibers in the hierarchy are usually also connected via corresponding feedback fibers, although with different distributional properties (Barone et al. 2000; Budd 1998; Felleman and Van Essen 1991; Rockland and Pandya 1979; Salin and Bullier 1995). These feedback connections provide a mechanism by which later visual areas, such as those in the inferotemporal cortex, can potentially modulate activity in neurons in early visual areas.

These organizational aspects of the primate visual system, and others not covered here, have guided neurally inspired depictive theories of visual mental imagery (cf. Kosslyn 1994). The key idea is that the precise spatial layout of objects is stored only implicitly in a distributed code in the inferotemporal cortex and that this layout can only be made explicit during visual mental imagery by recreating the corresponding pattern of retinotopic activation in early visual areas via feedback connections (Kosslyn 1994). Since neurally grounded depictive theories posit a key role for retinotopically organized visual areas in visual mental imagery, evidence that such brain areas are used during visual mental imagery would provide strong support for these theories.

2.5 The Functional Role Played by the Retinotopic Organization of Early Visual Cortex

Before discussing specific studies, it is important to counter two arguments often made against neurally inspired depictive theories of visual mental imagery. The first argument is that the retinotopic organization of early visual cortex is epiphenomenal and serves no functional role for visual imagery, and possibly even for visual perception. According to this argument, the relationship between retinotopic organization and visual mental imagery is accidental (Pylyshyn 2002) and akin to that between hard drive access processes on a computer and the LED that signals such access: Although the state of the LED correlates perfectly with hard drive access, it has no functional role in the working of the computer, and the computer would keep working properly without the LED. This criticism is refuted by evidence that the topographic organization in early visual cortex has a functional role in visual processing. First, damage to discrete portions of early visual areas produce visual scotomas (i.e., blind spots) in corresponding parts of the visual field, and the extent of the damage is systematically related to the size of the scotoma (e.g., Chiang et al. 2004). Second, TMS stimulation of discrete portions of early visual cortex can produce

faint visual sensations known as phosphenes in the corresponding parts of the visual field (Elkin-Frankston et al. 2011; Siniatchkin et al. 2011). Asking people to draw the perceived phosphenes during TMS stimulation enables researchers to determine the relationship between phosphene properties (e.g., their location, shape, and color) and stimulation parameters (e.g., TMS location and intensity). For instance, Kammer and collaborators were able to induce predictable shifts in the perceived location of phosphenes by shifting the TMS coil systematically over the occipital lobe in neurologically normal subjects (e.g., Kammer et al. 2005b). At higher TMS intensities, they were also able to produce scotomas (identified by asking people to detect small squares at various locations in the visual field and by determining at what locations detection rates were reduced) within the same regions of the visual field (e.g., Kammer et al. 2005a, b).

The second argument is that this retinotopic organization is not a geometrically accurate representation of the visual field, and so it cannot possibly provide useful depictive information about the visual world. For example, the same visual stimulus has a much larger cortical representation when it falls on the fovea than on more peripheral parts of the visual field because of the cortical magnification distortion (Sereno et al. 1995). Furthermore, in addition to deformations due to eccentricity, there are discontinuities in the visual maps, for instance, along the representation of the horizontal meridian in V2 and later areas (Felleman and Van Essen 1991). This is not a critical problem for neurally based depictive theories of visual mental imagery because early visual cortical areas are only one node in a large network (Felleman and Van Essen 1991) and the information they represent is decoded by other brain areas.

2.6 Visual Mental Imagery and Early Visual Cortex: Brain Imaging Findings

Two original studies using PET revealed that area V1 is recruited during visual mental imagery and that the pattern of activation is as predicted by the known retinotopic organization of this area. The first study (Kosslyn et al. 1993), leveraged the systematic representation of eccentricity in area V1. Blood flow was monitored with PET, while participants visualized capital letters at either a very small size (as small as they could visualize them) or at a very large size (as large as they could, while still being able to visualize the entire letter). The participants were asked to maintain the image for four seconds and then to make a judgment about the geometric properties of the letter (e.g., whether it had any straight lines). The rationale was that, if visual mental imagery uses topographical representations in area V1, then large visual images should engage parts of area V1 that are involved in representing more eccentric regions of the visual field located in increasingly anterior regions along the calcarine sulcus. Consistent with this prediction and with the retinotopic organization of area V1, results showed stronger activation in anterior parts of area V1 when participants visualized large letters and in more posterior parts when they visualized small letters. The second study used a similar logic but with different experimental stimuli (Kosslyn et al. 1995). During the PET session, participants

visualized line drawings of objects they had studied in advance within boxes of different sizes: small, medium, and large. To make sure participants were actually carrying out visual mental imagery, the task involved performing various visual judgments on the images (e.g., whether the left side of the pictures they had studied was higher than the right side). The results, again, nicely confirmed the predictions based on the representation of eccentricity in V1.

These initial findings have been replicated and extended in fMRI studies conducted in the last decade, overcoming the low spatial resolution of PET. An event-related fMRI study investigated whether visual mental imagery elicits activation consistent with the topographic representation of polar angle in early visual cortex (Klein et al. 2004). In this study, six participants either looked at bow-tie stimuli (perception) or visualized them (visual mental imagery) in independent blocks of trials. The stimuli were either vertical or horizontal, and each orientation was associated with a different auditory tone to indicate which stimulus to visualize during visual mental imagery. During the perception condition, participants pressed a key to report the orientation of the bow-tie stimuli, whereas during the visual mental imagery condition, they pressed a key as soon as they had formed a vivid image of the bow-tie stimulus indicated by the auditory tone at the beginning of each trial. Results revealed significant activation in area V1 in five out of six participants when visual imagery (eyes closed) was contrasted with a baseline defined by BOLD activation during the periods between trials. However, this comparison revealed no topographic differences between visual mental imagery of horizontal versus vertical bow-tie stimuli. This absence of retinotopic effects was hypothesized to be due to a large, nonspecific activation in early visual cortex in the task, possibly due to visual attention. A follow-up analysis tested this hypothesis and eliminated such nonspecific activation by contrasting activation between the horizontal and vertical bow-tie stimuli directly. And in fact, this direct comparison showed the expected retinotopic differences in V1 and V2. The effects found in the study, however, were rather weak (the significance threshold for the contrast was set at 0.01, uncorrected, with four voxel clusters), with only four out of six participants showing a significant overlap between voxels active during visual imagery and perception in the corresponding conditions. The individual variability of the results is consistent with other findings about individual differences in brain activation during visual mental imagery (e.g., Ganis et al. 2005; Kosslyn et al. 1996).

Another study employed standard retinotopic mapping methods (Sereno et al. 1995) to determine whether visual mental imagery elicits activation consistent with the representation of polar angle in visual cortex (Slotnick et al. 2005). The stimuli were rotating checkerboard "bow-tie" shapes. During the visual perception condition, six participants fixated the center of the display and pressed a key every time a small red square was flashed inside the revolving bow tie. During the visual mental imagery condition, the stimulus was made up of two thin arcs, outlining the outer edges of the bow tie. The task was to visualize the rest of the pattern and, again, to press a key when a small red square was flashed inside the region that the bow tie (now only visualized) would occupy. There was also a control attention condition (within participant), during which all parameters were identical to the imagery condition with the difference that participants were not instructed to create visual

mental images, but only to wait for the red square and to press a key depending on whether it was presented to the left or to the right of fixation. Results for the imagery condition showed small activation foci in V1 that were not observed in the control attention conditions in three out of six participants. Activation in extrastriate regions was observed in four out of six participants. Although there was—for some participants—topographically organized activation that was not found in the control attention condition described earlier, the majority of the imagery-induced activation overlapped with activation induced by visual attention, which could indicate that spatial attention may function as a scaffolding for visual imagery.

A more recent study (Thirion et al. 2006) used machine learning methods and an "inverse retinotopy" approach to extract information from single fMRI trials during visual perception and visual mental imagery. This approach inverts the mapping between visual space and visual cortex to estimate the actual visual stimulus that would be most likely to have generated a given pattern of activation in early visual cortex. During the perception condition, nine participants looked at patterns of rotating Gabor patches (there were a total of six possible patterns), whereas during the visual mental imagery condition, they chose one of the six patterns and visualized it to the left or right of a fixation point, depending on the direction of a probe arrow that was presented on each trial. The results showed an average of over 80% classification rates for the perception conditions (chance was 1/6, 16.7%, given that there were six possible patterns). All hemispheres examined showed robust classification performance (between 70 and 96%, using a leave-one-out classification method). Most of the voxels that contributed to successful classification were located in area V1 (50–60%), followed by area V2 (20%), which is not surprising, given the topographic characteristics of these areas discussed earlier. The results were much weaker for the visual mental imagery condition: With averaged data, the imagined pattern could be correctly predicted only using data from 5 hemispheres out of 16, and even these cases were rather marginal. Low generalization to imagery was also found for trial-specific analyses, (min 38%, max 67%, using a leave-one-out classification scheme and a Bonferroni correction for multiple comparisons). Additional studies on this issue will be reviewed in Chap. 15.

Thus, these results provide evidence in favor of the claim that mental images of shapes sometimes activate topographically organized areas in early visual cortex. However, the signals observed are much weaker than for visual perception, and usually they are difficult to detect in individual participants.

2.7 V1 Recruitment During Visual Mental Imagery: Potential Inconsistencies in the Neuroimaging Literature

Although numerous studies have shown early visual cortex engagement during visual mental imagery, some studies have failed to observe such engagement (Kosslyn and Thompson 2003). Since many paradigms and methods were used in different studies, one way to try to figure out which factors may be reliably associated with activation in early visual cortex during visual mental imagery is by carrying

out a meta-analysis of the literature. In one meta-analysis of this type (Kosslyn and Thompson 2003), three theories were described that could account for the observed activation in early visual cortex (areas V1 or V2) during visual mental imagery. The first theory, referred to as "perceptual anticipation theory," was the depictive theory of visual mental imagery described earlier (Kosslyn et al. 2006). The second theory, "propositional theory," was the type of non-depictive theory put forward by Pylyshyn (1981), which predicts no activation in early visual cortex during visual mental imagery, and it postulates that activation in this area, if observed, is purely artifactual. The third theory, referred to as "methodological factors theory," postulates that activation in early visual cortex is always present during visual mental imagery, but is not detected in some studies because of methodological issues.

The meta-analysis classified the visual mental imagery tasks used in 59 neuroimaging studies of visual mental imagery according to six variables: use of high-resolution details, use of shape judgments (vs. spatial judgments), use of exemplars (vs. prototypes), number of participants, neuroimaging technique, and use of a resting baseline (vs. a more controlled baseline in which participants perform a well-defined task not involving visual mental imagery, rather than an uncontrolled resting task). Perceptual anticipation theory predicts early visual cortex activation when using high-resolution details and shape judgments of specific exemplars. In contrast, propositional theory predicts that visual mental imagery never engages early visual cortex. According to this theory, any activation observed in early visual cortex during visual mental imagery is artifactual and caused by factors such as small numbers of participants, less powerful techniques, and a resting baseline (all factors that increase the chance of false positives). The methodological factors theory predicts the opposite, namely, that activation in early visual cortex is present regardless of the type of visual mental imagery. This theory also predicts that the only factors that determine whether this activation will be detected or not are methodological. For instance, (real) activation in early visual cortex would be more likely to be detected by using larger numbers of participants. Although these factors also apply to perceptual anticipation theory, methodological factors theory postulates these are the *only* factors that would make a difference.

A theory-driven regression analysis revealed that early visual cortex activation was predicted by four variables, two associated with perceptual anticipation theory (use of high-resolution details and shape judgments) and two with methodological factors theory (use of more powerful brain imaging technique and non-resting baseline). The non-resting baseline finding is consistent with findings that resting baselines (e.g., simple fixation) can cause activation increases in early visual cortex, thereby canceling out the small increases that may occur during visual mental imagery (Kosslyn et al. 1995).

An exploratory analysis was also conducted (Kosslyn and Thompson 2003) in which the presence or absence of early visual cortex activation across studies was correlated with 15 additional variables (for a total of 21). Results showed that 9 out of these 21 variables were correlated with early visual cortex activation across studies. Since some of these variables were correlated with each other, a forward stepwise logistic regression on these results showed that the use of high-resolution details and shape judgments in the task, and the neuroimaging technique employed reliably

predicted activation in early visual cortex, consistent with the results of the theory-driven regression analysis.

The finding that high-resolution details are key for recruiting early visual areas makes sense because of the high-resolution topographic organization of these areas. Later areas, such as V4, have much coarser retinotopic organization than V1 and V2, and so they may not be able to support tasks requiring the visualization of fine details. Furthermore, the importance of using shape judgments (as opposed to spatial ones) can be understood by remembering that visual memories about shapes are stored in inferotemporal cortex by means of a distributed code (Tanaka 1996; Lehky, et al. 2011) that does not make spatial layout explicit; this spatial layout can be made explicit by reconstructing the image in early visual cortex. In contrast, spatial judgments may be stored already in a suitable code in retinotopically organized areas in the parietal cortex (Saygin and Sereno 2008; Sereno et al. 2001), and so they may not require early visual cortex.

In sum, these findings indicate that the apparent inconsistencies in the neuroimaging literature about early visual cortex activation during visual mental imagery may not be due to random factors, but to systematic variables that can be manipulated.

2.8 Visual Mental Imagery and Early Visual Cortex: Findings in Neurological Patients

If early visual cortex is indeed required for carrying out at least some forms of visual mental imagery (those involving high-resolution images of shapes, as just discussed), then patients with damage to this part of the cortex should be impaired at these types of visual mental imagery. Neuroimaging measures activation in a brain region during a given task, but it leaves open the possibility that such activation is only *correlated* with the performance of the task, but plays no functional role.

As mentioned earlier, unilateral focal damage to V1 produces scotomas in small parts of the visual field that are represented by the damaged cortical tissue. If the damaged region is large and encompasses both hemispheres (for instance, because of posterior cerebral artery infarct), then the result is cortical blindness. If early visual cortex is necessary for visual mental imagery, then such damage should impair some forms of mental imagery.

Although this logic seems straightforward, there are important limitations in the type of inferences that can be made from data from neurological patients. First, one cannot be sure that brain tissue that looks normal is functionally normal because some abnormalities may not be detectable with the technique employed (e.g., these abnormalities may be at a scale that is smaller than the voxel size used). Second, brain damage is not a variable that can be manipulated experimentally because we cannot control the location or size of the lesion and large lesions can affect nearby regions that nonetheless carry out different functions, potentially leading to the incorrect inference that these functions are related. Third, the brain is not a static organ, and damage can trigger compensatory mechanisms

(e.g., Barbay et al. 2006; Dancause et al. 2005) such as when other areas attempt to compensate for lost functions, further complicating the interpretation of the findings. Fourth, in most published patient studies, performance on visual mental imagery tasks has not been assessed rigorously. For example, the time patients take to respond is rarely measured. Finally, the literature consists largely of single-case studies that cannot be replicated in principle because patients may not be available to other groups or because the specific impairment may be short lived. This is clearly a major methodological issue that can only be resolved by pooling resources and increased sharing of patients among interested groups.

Despite these limitations, cases have been described in which visual mental imagery is impaired as a result of damage to the occipital cortex. Patients with hemianopia (i.e., blindness in one-half of the visual field, following damage to one cerebral hemisphere) are particularly relevant because it is possible to administer a visual mental imagery task in the functioning hemifield and compare the results with the same task in the impaired hemifield within the same individual. In an elegant study using this logic, eight hemianopic participants were tested on a mental scanning task, an objective test of visual mental imagery, which is rare in the assessment of visual mental imagery in patients (Butter et al. 1997). Participants were shown a pattern of four dots, and subsequently, after the pattern had disappeared, they were asked to decide whether an arrow pointed at a location previously occupied by one of the dots. Compared to healthy controls, patients showed the expected pattern: lower accuracy when the arrow pointed at a dot in the hemifield that was affected compared to when it pointed at a dot in the intact hemifield. Several control conditions ruled out potential confounds such as that the patients were unable to see the dot pattern or the arrow to begin with. A limitation of this study is that only computed tomography scans were performed, and only on a subset of the patients, which makes it impossible to know the extent to which the brain damage affected early visual cortex. Other limitations are discussed in Chap. 13, which also reports recent evidence at odds with the findings by Butter and collaborators, a clear indication that more systematic research on this issue is needed. The findings from the study by Butter and collaborators dovetailed with those obtained in an earlier study by Farah and collaborators in a single patient after removal of the occipital lobe in one hemisphere (Farah et al. 1992): In this patient, the horizontal extent of visual images was reduced in half after the surgery, whereas the vertical extent was normal and consistent with the fact that the representation of half of the horizontal meridian was lost.

There are also cases in the literature that may seem to contradict neurally inspired depictive theories. In some of these cases, widespread damage to early visual cortex, including V1, results in cortical blindness but does not seem to impair visual mental imagery. One of the most striking cases is that of a young woman who became cortically blind after a stroke that damaged her primary visual cortex bilaterally (Chatterjee and Southwood 1995). Despite her blindness, apparently she could carry out many visual mental imagery tasks including some that involved judging the shape of capital letters or common animals or drawing common objects from memory. She also reported using visual mental imagery during her high school studies (which she completed after becoming cortically blind). There have been other cases of cortical blindness and apparent sparing of visual mental imagery abilities

(Goldenberg et al. 1995), but the tests used to assess visual mental imagery often have been rather crude (Bartolomeo 2002).

Cases such as these, however, do not constitute strong evidence against the hypothesis that V1 is needed to perform at least certain types of visual mental imagery for reasons that go beyond the methodological issues summarized earlier (see also Chap. 13). First of all, especially with the low-resolution brain scans used in the past, it is difficult to rule out that spared parts of early visual cortex were still functioning normally in these patients. This is an important point because brain imaging studies of visual mental imagery usually show activation in only small portions of V1 (e.g., Slotnick, et al. 2005) relative to visual perception conditions. Second, many of the tasks used to test visual imagery may have not been sufficiently sensitive or may have not recruited V1 to begin with. For example, imagery questions such as whether the body of a snake has curved parts may be answered by using information stored in semantic memory and may not require high-resolution imagery. In addition, imagery tasks involving stimuli with an overlearned motor component, such as drawing letters or drawing simple objects, may be carried out using information stored in the motor system (e.g., James and Gauthier 2006). Third, many visual mental imagery tasks may be carried out by using late visual areas or even areas that are not involved in vision per se. For example, as discussed earlier, if a particular task does not require discriminating high-resolution details in the visual image, then V1 may not be necessary and later areas may be able to support adequate performance on the task. In such a task, damage to V1 should not disrupt the ability to perform imagery tasks.

Finally, how can we explain that some patients who are cortically blind, such as the patient described by Chatterjee and Southwood, claim to have vivid mental imagery? Critically, these types of introspective reports do not prove that these patients can actually use visual mental images in memory and reasoning any more than the introspective feeling one has of being able to perceive all details of a visual scene proves that we actually perceive them; in fact, there is evidence that we perceive only few details of the visual world at any time (Rensink 2002). This is because the subjective experience of having a vivid mental image may reflect only in part activation in visual cortex and is probably the product of processes taking place in many other brain areas.

2.9 Visual Mental Imagery and Early Visual Cortex: Virtual Lesion Findings

One of the few techniques for testing the functional role of a brain region (in a particular task) is TMS. With this technique, a coil is used to deliver magnetic pulses to a targeted brain region, creating slight disruptions of neural activity for a short period (from milliseconds with single-pulse TMS to a few minutes with repetitive TMS). The advantages of TMS are that the stimulation can be controlled precisely, the disruption is reversible, the impairment is too short lived to allow compensatory

phenomena to take place, and one can easily conduct studies on large groups of people instead of having to rely on single cases. More details about using this technique to study mental imagery are provided in Chap. 15. Perhaps the most convincing TMS study showing that early visual cortex is necessary for both visual perception and high-resolution visual mental imagery (Kosslyn et al. 1999) used low-frequency repetitive TMS, which is known to decrease cortical excitability for several minutes after stimulation (Muellbacher et al. 2000; Siebner et al. 2000). In the perception condition, five participants were asked to compare attributes of four sets of black-and-white stripes, arranged into four quadrants. The stripes varied in length, width, spacing, and orientation. In the imagery condition, the task was identical (e.g., the participants compared the relative lengths of stripes in two specific quadrants), but the same participants had to visualize the visual pattern array. A parallel PET study had shown that visual mental imagery of these same stimuli elicited activation in early visual areas. Stimulation was delivered either to these early visual areas by targeting the occipital pole (real-TMS condition) or directing the coil away from the brain (sham-TMS control condition). Results showed that real TMS (compared to sham TMS) slowed down responses in both the perception and imagery conditions, supporting the idea that early visual cortex is necessary to perform visual mental imagery.

2.10 Visual Mental Imagery and Late Visual Areas in the Ventral Stream

Early visual areas provide input to visual areas in the ventral stream (which processes object properties such as shape, texture, and color). Studies in neuroimaging and neurological patients have shown that there is spatial segregation in the representation of at least some object classes (Downing et al. 2006; Kanwisher and Yovel 2006) but also that visual objects are represented in a spatially distributed manner in these cortical areas (Haxby et al. 2001). For example, some patches of cortex in the lateral fusiform gyrus are selective for images of faces, relative to other object categories (Kanwisher and Yovel 2006), and, similarly, patches of cortex in the medial fusiform and parahippocampal gyri respond more strongly to pictures of buildings than to images of other objects (Downing et al. 2006). Next, we will review briefly the empirical evidence that this organization also characterizes the system used during visual mental imagery of objects.

2.11 Late Visual Areas and Visual Mental Imagery: Brain Imaging Findings

Although the causes and function of the spatial segregation in the ventral stream (Hasson et al. 2003; Levy et al. 2004) are still under debate, this organization can be exploited to further address the issue of the similarity between the processes and

representations recruited during vision and visual mental imagery. Accordingly, several studies have used this logic by comparing the spatial pattern of brain activation in ventrotemporal cortex during visual identification of objects and visual mental imagery of these same objects (Ishai et al. 2002; 2000; Mechelli et al. 2004; O'Craven and Kanwisher 2000). In the first of such studies, eight participants recognized pictures of familiar faces and buildings or they visualized them (O'Craven and Kanwisher 2000). During the perception blocks, a contrast between stimulus category conditions revealed a clear segregation in ventrotemporal cortex between activation elicited by faces and buildings. This pattern was paralleled by the results in the imagery condition, but activation was much weaker than that observed during perception (50% weaker, on average) and encompassed much smaller regions (17% for faces and 39% for buildings, relative to the number of voxels active in the corresponding perception conditions). Furthermore, almost all the voxels that were active during visual mental imagery were included in the regions that were active during the corresponding perception condition (84% for faces and 92% for buildings). Finally, in the visual mental imagery condition, there was considerable individual variability. For instance, only four participants out of eight showed face-specific activation during imagery. This is consistent with the individual variability observed in many of the V1 activation studies of visual mental imagery described earlier (e.g., Thirion et al. 2006). In a similar study (Ishai et al. 2000), nine participants were tested in visual perception and imagery conditions. During the main perception condition, participants passively viewed pictures of faces, houses, and chairs in independent blocks. During the main visual mental imagery condition, they visualized familiar faces, houses, or chairs while looking at a gray background. Perception and imagery baseline conditions involved passive viewing of scrambled versions of the pictures used in the perception condition and the same gray background used in the imagery condition, respectively. After removing the respective baselines and comparing the three stimulus types, researchers found several regions in the ventral stream that showed differential responses to pictures of faces, houses, and chairs. Critically, about 15% of voxels in these regions showed a similar pattern during visual mental imagery. This confirms the finding by O'Craven and Kanwisher (2000) that only relatively small subsets of voxels in regions that respond differentially during visual perception show the same pattern during imagery. Interestingly, activation during visual mental imagery (compared to the control condition) was also found in parietal and frontal regions, but no corresponding activation was observed during the perception condition, probably reflecting the stronger engagement of top-down processes during visual mental imagery than perception.

A follow-up fMRI study contrasted visual perception and imagery of famous faces (Ishai et al. 2002). In the perception condition, nine participants were shown pictures of famous faces, whereas in the baseline perception condition, participants saw scrambled pictures of faces. In the visual mental imagery conditions, participants visualized famous faces against a blank screen, following a written probe name. Participants were trained on half the faces immediately prior to the study,

whereas they relied on their preexisting long-term memories for the other half. Furthermore, for half the blocks (attention condition), they made a judgment on a feature of each face (e.g., whether it had a large nose), whereas no task was used for the other half. During the baseline imagery condition, participants saw letter strings and passively viewed a blank screen.

Results confirmed previous findings by showing activation in the lateral fusiform gyrus during face imagery in a subset of voxels (about 25%) active during face perception. This activation was stronger for faces that had been studied just before the scan. Attention modulated activation in regions outside the ventral stream: the intraparietal sulcus and the inferior frontal gyrus. A more recent study reanalyzed a subset of these data, trying to understand differences in the connectivity of category-specific late visual areas within a large-scale network during visual perception and imagery (Mechelli et al. 2004). Results showed that functional connectivity to late visual areas was strongest from early visual areas during perception, but strongest from frontal and parietal regions during visual mental imagery. This indicates that the functional role of the same late visual areas changes depending on whether the task is visual perception or imagery. Additional studies on this topic are described in Chap. 15.

One potential explanation for the weaker and less reliable signals and smaller foci of activation during imagery than perception is that the feedback signals generated during visual mental imagery are less strong than the feedforward signals generated during visual perception. This idea is consistent with the generally more diffuse organization of feedback projections (Budd 1998), which may suggest that fewer neurons are driven by such signals. After all, introspectively, visual mental images are much "fainter" than percepts, which is probably one way that the visual system can distinguish percepts from visual images. Another possible explanation, not mutually exclusive with the first, is that some of the regions activated in ventral cortex only during the perception conditions may reflect various perceptual processes—such as feature analysis and high-level grouping of visual features—that are not fully engaged during imagery.

An important question is whether these similarities between visual perception and imagery in late visual cortex hold at the single-neuron level. The only technique that enables us to address this question involves recording the intracranial electroencephalogram. Patients with epilepsy resistant to pharmacological treatment may decide to undergo surgical resection of the affected areas, and in some cases, chronic electrodes are implanted in their brain to measure brain activity during seizures, allowing the surgeon to determine the location of affected areas. Between seizures, researchers can collect data from these patients in experimental paradigms. One such study compared visual perception and imagery, recording activity from 276 single neurons (from a total of nine patients) in the medial temporal lobe, including the parahippocampal cortex (Kreiman et al. 2000). Results showed that a small subset of neurons responded to both visual stimuli and visual mental imagery of the same stimuli. Furthermore, the pattern of selectivity was very similar in the two cases, indicating that the similarities seen at the macroscopic level in these regions are also present at the single-neuron level.

2.12 Late Visual Areas: Findings in Neurological Patients

The neuroimaging data just discussed are generally consistent with data from patients with damage to late visual areas in the ventral stream (Ganis et al. 2003). Given the relative spatial segregation in the ventral stream of visual object representations, one could predict that some neurological patients should exhibit problems visualizing certain classes of visual stimuli but not others, depending on the site of the damage. In addition, because of the similar spatial segregation for visual mental imagery and visual perception, patients should show parallels in the patterns of impairment during visual perception and visual mental imagery. As expected, patients have been described with domain-specific deficits in visual perception and with parallel deficits in visual imagery. For example, some patients are impaired at identifying faces (prosopagnosia) but not other objects—and they are also impaired at tasks involving visual imagery of faces (Shuttleworth et al. 1982; Young et al. 1994). A single-case study reported a patient who exhibited a selective deficit in identifying animals and showed a parallel deficit when asked to describe animals or to draw them from memory (Sartori and Job 1988). An early review of the patient literature (Farah 1984) described 28 cases of object agnosia and reported that in 14 cases, there was a parallel visual imagery impairment. The remaining cases were either not tested for imagery or the imagery tests were not sufficiently rigorous.

At least some of these parallel deficit cases can be explained by assuming damage in brain regions that support long-term visual memories for objects and faces stored in later visual areas; such areas would be used during both visual perception and visual imagery. Given that the clusters of activation in late visual areas elicited by visual perception are much larger than those elicited by imagery (and usually encompass them), dissociations should result from damage to the unshared portions of these areas. Indeed, some patients with visual agnosia have also been observed with relatively normal visual mental imagery (Bartolomeo et al. 1998; Behrmann et al. 1994; Servos and Goodale 1995). Although some dissociation cases can be attributed to crude visual mental imagery testing (as seen in our discussion on early visual areas), some patients could carry out rather challenging visual mental imagery tasks (Servos and Goodale 1995). Another possible explanation is that these patients sustained damage to other ventral regions that are necessary for visual perception but not for visual mental imagery. These regions may be important for grouping and other perceptual processes that are needed for identifying objects but not for visual mental imagery (Behrmann et al. 1994). Finally, there is sparse data on a few cases with normal visual perception but impaired visual mental imagery (Farah 1984; Goldenberg 1993). Damage to inferior frontal and intraparietal regions that modulate activation in the ventral stream during visual mental imagery (Mechelli et al. 2004) may explain some of these cases, but more research needs to be done to draw meaningful conclusions from these dissociations.

2.13   Conclusions

The development of cognitive science and neuroscience has resulted in substantial and ongoing progress in the investigation of visual mental imagery. Cognitive science and neuroscience tools and paradigms have enabled researchers to study visual mental imagery more objectively than was possible by using purely introspective methods. Furthermore, the huge and rapidly expanding knowledge based on the organization and working of the primate visual system (human, in particular) has been providing key information for generating more detailed theories of visual mental imagery. However, this progress has also revealed important holes in our grasp and conceptualization of visual mental imagery processes. First, we still know very little about the commonalities and differences between neural processes supporting visual mental imagery and other cognitive processes such as selective or spatial attention and working memory. Second, the neural causes of individual differences in visual mental imagery observed in many studies are still poorly understood. Third, despite numerous single-case studies, systematic investigations of visual mental imagery using rigorous tests in groups of neurological patients are still lacking (see Chap. 13 for evidence of progress in this direction). Fourth, there has been only very limited effort toward developing computational neuroscience theories of visual mental imagery; such theories are necessary to generate predictions to test theories of visual mental imagery and its neural implementation.

Progress in filling these and related research gaps will require continued interdisciplinary collaborations involving psychologists, neuroscientists, and computer scientists of the type we have been witnessing in cognitive science over the last three decades.

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Chapter 3
Somesthetic Mental Imagery

Alberto Gallace

Abstract The ability to create and manipulate images arising from our sense of touch has been far less investigated by the scientific community as compared to the same ability in the visual domain. Most of the studies that directly addressed this topic have compared performances in sighted and visually impaired individuals. Moreover, the large majority of these studies have investigated tactile mental imagery by using similar procedures to those previously adopted by studies of visual mental imagery. This approach has certainly led to important findings, but has also resulted in a scarcity of insights into certain important aspects that are peculiar to the tactile sense. In particular, the question related to the integration of all the different sources of information that enter tactile processing, such as signals from proprioception, pressure, thermic, and noxious receptors, has been largely neglected by the literature on mental imagery so far. This chapter critically discusses the results obtained by the extant research on tactile imagery, in an attempt to highlight its limitations and to define the possible directions that will need to be explored by researchers in the future.

Keywords Tactile • Haptics • Mental imagery • Pain • Somatosensory • Body

3.1 Introduction

The first approach to the concept of mental imagery based on sensations that arise from our sense of touch (somesthesis) is certainly not an easy one. In fact, any reader, whether he/she belongs to a scientific audience or not, may well find the

A. Gallace, Ph.D. (✉)
Department of Psychology, University of Milano-Bicocca,
Piazza dell'Ateneo Nuovo 1, Milan 20126, Italy
e-mail: alberto.gallace1@unimib.it

term "tactile imagery" somehow awkward, an expression that combines contradictory terms. "Tactile" clearly relates to our sense of touch, our ability to discriminate the presence of stimuli on the surface of our body by means of specific classes of receptors (a term that is well differentiated from "haptic" that relates instead to the active exploration of stimuli by using our sense of touch; see Loomis and Lederman 1986). "Imagery" derives from the Latin word "imago," image indeed, but also appearance, echo, ghost, and phantom. What, then, is a "tactile image"? What is really represented in it? And what does and does not contain a tactile image? Our everyday experience can be of help here. If we close our eyes and think about a seaside holiday in the past, we can certainly remember the sensations elicited by our feet lying on the beach on a sunny day. But what we do actually "remember"? Is it only the vision of our feet stuck into the sand or rather also those tickling sensations produced by the tiny grains of sand? Is it the pleasant warmth on our skin? The pain caused by some sharp shells? The comfortable position of our body? All of these sensations are likely to enter the tactile images associated with our experiences. In fact, mental imagery derived from our sense of touch cannot be restricted solely to manual interactions with objects and how they feel when held in our hands but includes a wide range of skin sensations, pain, and even representations of the body.

In our everyday life, we use visual imagery in a number of different situations (such as when we try to remember where we left our car keys; see Kosslyn et al. 1990, for other examples), but we rarely tend to think about tactile imagery (at least explicitly). Despite this apparent neglect, we are perfectly capable of using it, regardless of whether we are sighted or visually impaired. Just as we can say whether the sweater that we are wearing now is a different color to the one that we wore yesterday, we can also use tactile imagery to say without doubt whether it is softer or rougher, warmer or colder, and heavier or lighter.

Tactile imagery is certainly far less investigated than mental imagery in other sensory modalities, such as vision and audition (Fig. 3.1). This is likely due to a number of factors, including the greater technical difficulties in studying touch as compared to studying vision and audition, but also to a number of theoretical problems related to the ways in which tactile and haptic mental imagery can be tested. While technical difficulties have been more recently overcome by the rapid progresses in technology (e.g., Gallace et al. 2007b; Gallace et al. 2011), theoretical problems related to the study of tactile mental imagery still affect research in this field.

It should be noted that there are, at least, two fundamental ways of studying tactile imagery. First, the "visually driven" approach involves the application of the same (or similar) theories, methods, and paradigms adopted in visual mental imagery research to study tactile imagery and is the most frequently adopted method of studying tactile imagery to date. Its main advantage is that it can build upon the much wider knowledge base regarding visual information processing, as compared to the more limited knowledge on tactile information processing. Moreover, this approach complements research on multisensory information processing. In fact, multisensory research has convincingly suggested in the last couple of decades that
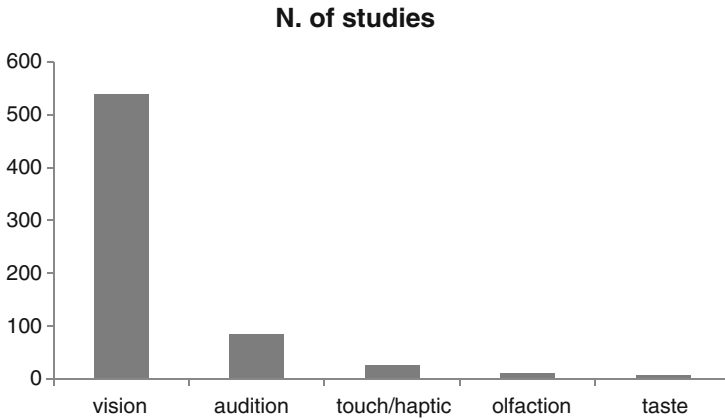
N. of studies

Fig. 3.1 Approximate number of studies that have addressed the topic of mental imagery in different sensory modalities to date. The research was performed on the Scopus database by calculating the occurrence of the terms "mental image" or "mental imagery" and (1) vision or visual; (2) auditory or audio; (3) tactile or haptic; (4) olfactory or olfaction; (5) taste or gustatory, in the abstract only

a number of higher order cognitive mechanisms might be similar (if not shared) among different sensory modalities (e.g., Calvert et al. 2004; Lacey et al. 2009; Spence and Driver 2004; see also Ghazanfar, and Schroeder 2006). However, the visually driven approach fails to consider those aspects of the tactile cognitive system, such as the interactions between proprioception, body representation, temperature, and pain processing (just to cite a few of them), that are peculiar to this sensory modality. As a consequence, the visually driven approach often results in comparisons between the limitations of visual and tactile imagery and/or comparisons between the abilities of sighted and visually impaired individuals to perform similar tasks (e.g., Aleman et al. 2001; Marmor and Zaback 1976; Ungar et al. 1995; see also Dulin et al. 2008). A second and more pioneering method of studying tactile mental imagery, the "tactile-driven" approach, investigates the tactile sense without necessarily looking for comparisons with the other senses. This is a relatively unexplored approach, but it is likely to generate important and interesting discoveries in the field of tactile imagery in the near future. This review will try to consider both aspects whenever possible.

This chapter will show that our knowledge regarding tactile and haptic imagery is very limited, especially if compared to visual or auditory imagery. Moreover, as we have mentioned above, most of this knowledge derives from studies that were actually more interested in studying the performance of visually impaired participants than the neurocognitive basis of tactile imagery in the sighted population. While some of these important studies will be reviewed here, the importance of looking to other research areas related to mental imagery, such as tactile working memory, the limits of tactile awareness, or the relationship between mental imagery

and the representation of the body, will be highlighted. In fact, the knowledge arising from these fields of study is likely to generate important inferences regarding some important aspects of tactile imagery that have not been considered so far. After an overview of the results of the studies that have investigated tactile imagery in sighted and visually impaired participants, this chapter will tackle the theoretical problems that arise when attempting to compare visual and tactile mental imagery. The relevance of a number of topics, such as synesthesia, hallucinations, and body representation to the study of tactile mental imaging will also be discussed. In an attempt to highlight under-investigated aspects of tactile mental imaging, this chapter will also analyze recent research on "pain imagery," trying to define its future directions and goals.

3.2 The Ability to Generate and Manipulate Mental Images Based on the Sense of Touch in Sighted Participants

Research on vision has adopted a number of paradigms in order to study people's ability to generate, retain, and explore mental images. One of these paradigms relates to the mental rotation of objects or displays. In a typical mental rotation task, the participants are required to decide what figure among a number of distractors corresponds to a given sample figure. Given that the sample figure and the target vary only in terms of degree of rotation across their center, in order to perform the task, the participants need to mentally rotate the sample in order to align it with the target (e.g., Marmor and Zaback 1976; Shepard and Metzler 1971). In general, the participants' reaction times to this task are linearly related to the rotation angle, suggesting that people mentally rotate the stimuli in an analogical way. Mental rotation of objects perceived haptically has been investigated in a number of studies (see Prather and Sathian 2002, for a review). In such studies, a large variety of stimuli have been used, including raised dot patterns that represent abstract forms (Dellantonio and Spagnolo 1990), alphanumeric stimuli (Rösler et al. 1993), cutout letters (Prather and Sathian 2002; Hunt et al. 1989), and geometric shapes (Marmor and Zaback 1976). The large majority of these studies have shown that, just as in vision, people's reaction times to these tasks are related to the difference between the angles of presentation of the two stimuli to be matched (but see Shioiri et al. 2011, for the report of no such effect in a task involving the matching of haptically explored two-line shapes).

It is relevant to consider here that the mental rotation of an object can be based on different frames of reference. For example, visual stimuli can be rotated as a function of an allocentric, gravitationally aligned, reference frame or in an egocentric, retinally aligned, reference frame (e.g., Corballis et al. 1978). As far as the tactile modality is considered, one may observe that whenever we touch an object, we establish a relation between "our hand" and the object. As a consequence, the orientation of the object with respect to the hand is processed. That is, information regarding a given haptically explored stimulus can be based on both hand-centered

and object-centered spatial frames of references. One might then reasonably wonder about what frame reference (e.g., allocentric, hand-centered, and body-centered) is adopted when haptic mental images are rotated. A study by Volcic et al. (2009) has directly addressed this question by asking the participants to assess the parity of two objects located in various spatial locations by exploring them with different hand orientations. They found that the mental rotation task was most affected by the hand-centered reference frame but that also the body-centered reference and allocentric frames of reference played an important role. In fact, none of these factors could be excluded without noticeably affecting accuracy. On the basis of these results, one might conclude that haptic mental imagery can be based on the interactions between multiple spatial reference frames rather than on a single reference frame.

Another task that is often used to study mental imagery in vision is related to "mental scanning" or "mental map navigation," where the participants are required to mentally go from one point to another of an imagined display (e.g., Kosslyn et al. 1978). Reaction times in this task are linearly related to the physical distance between the start and end points of the image (the farther the two points, the longer the reaction times). A number of studies have shown that the same distance effect can be found in blindfolded participants while maintaining images of haptically explored displays or maps (e.g., Afonso et al. 2010; cf. Röder and Rösler 1998). An important point to be considered here is that research on this topic has highlighted the fact that while blindfolded participants are perfectly capable of generating and scanning small size mental maps based on haptic exploration, they suffer from a reduced ability to generate precise spatial representations of full-scale navigable space (e.g., created by an immersive audio virtual reality system; see Afonso et al. 2010). This might be taken to suggest that the generation of mental images on the basis of haptic and locomotor input by sighted participants might be more limited than the ability to generate these images when visual and verbal input is provided. However, further experiments should be performed in order to verify if extensive practice in this task might also affect performance.

3.3 Tactile and Haptic Mental Imagery: A Comparison Between Visually Impaired and Sighted Individuals

As mentioned in the introduction, the most common approach to the study of tactile and haptic mental imagery involves testing the performance of both sighted and visually impaired individuals. The popularity of this approach is likely related to the fact that sighted individuals tend to use visual strategies in order to perform tactile imaging tasks (e.g., Kerr 1983; Uhl et al. 1994). Therefore, by testing early or congenitally blind participants, it is possible to exclude the possibility that visual mental imagery is used in the tactile task (see Bertolo 2005, on this point). For example, Aleman et al. (2001) investigated the ability of congenitally blind

individuals to perform tasks thought to be mediated by visual mental imagery in sighted individuals (see also Arditi et al. 1988; Kerr 1983; Uhl et al. 1994). The participants in their study had to perform a pictorial task, involving the mental comparison of the shapes of objects, and a spatial task in which they had to imagine a path through haptically explored 2D and 3D matrices. The results showed that although the blind participants performed somewhat less accurately than the sighted, they were nevertheless still able to perform both tasks reasonably successfully. This result can be taken to suggest that mental "images" can be used by both the sighted and the blind in those tasks requiring the comparison of object representations held temporarily in working memory. Moreover, the apparent similarity between the performance of the sighted and blind participants in these kinds of tasks might also lead to the suggestion that imagery representations rely very little on vision and are instead crossmodal or multisensory in nature (e.g., De Beni and Cornoldi 1988).

Other studies have shown that the blind experience mental imagery, although their ability to use specifically visual imagery decays with time in the case of acquired blindness and is probably totally absent in those born blind (e.g., Hollins 1989). It has also been shown that blindness, especially when congenital, slows the performance of tasks requiring the mental rotation of tactile stimuli (e.g., Marmor and Zaback 1976; Ungar et al. 1995). For example, Marmor and Zaback presented to a group of congenitally blind and blindfolded sighted participants a mental rotation task in which two consecutively presented 3D displays had to be compared. In this task, the second display was typically oriented differently from the first one across the three main spatial axes. As we have seen in the previous section, when this task is presented visually, the latency of a participant's response is linearly related to the degree of rotational misalignment between the two displays (i.e., the more the two stimuli are misaligned, the slower the reaction times; see Shepard and Metzler 1971; Wohlschläger and Wohlschläger 1998). The results by Marmor and Zaback showed that the blindfolded sighted participants responded more rapidly overall (and made fewer errors) as compared to the blind participants. This result was taken to suggest that while the congenitally blind are capable of forming mental images which are functionally equivalent to those of the sighted, visual images may simply be easier to manipulate than haptic images. It is, however, important to note here that using exactly the same task, Carpenter and Eisenberg (1978) failed to observe better performances in the sighted as compared to the blind and suggested that this apparent discrepancy might be due to possible differences in the amount of previous experience that congenitally blind participants may have with tactile graphical materials (i.e., tactile reproductions of visual images). That is, the large majority of the studies performed on visually impaired individuals would seem to suggest that tactile and/or haptic mental images are harder to manipulate than their visual equivalent. However, whether this limitation is due to the functioning of the systems subserving mental imagery (such as working memory) or rather to the role of practice with the stimuli presented is still a question that requires further research attention in the future.

3.4   Visual Imagery and Tactile Imagery: Theoretical Problems

One of the most influential theories of visual imagery is that proposed by Kosslyn (e.g., Kosslyn 1975, 1980, 1994; see also Kosslyn et al. 2006). Without going into the details of Kosslyn's theoretical framework, here it is important to highlight that visual mental imagery is not a unitary function, but the result of separate (and interacting) processes (e.g., Kosslyn and Shwartz 1977) responsible for generating the image, inspecting the image, maintaining the image over time, and eventually transforming the image (e.g., by rotating it along spatial dimensions). Each of these functions requires multiple mechanisms. For example, the generation of the image requires the activation of information stored in long-term memory and the construction of a temporary representation in short-term memory. One of the most important aspects of Kosslyn's theory is the hypothesis of a visual buffer (similar to the 2½D sketch of Marr's (1982) theory of vision) where a "quasi-picture" or "surface representation" is constructed and inspected (e.g., Kosslyn 1980, 1994).

As we have seen in the previous section, the extant literature has clearly demonstrated that blind people can perform similarly to sighted individuals in tasks involving the retention, inspection, and manipulation of tactile mental images (e.g., Kosslyn and Shwartz 1977; Kosslyn et al. 1985; see also Bertolo 2005). That is, similar mechanisms might support performance in both groups of participants. However, the fundamental problem here is that in Kosslyn's theory, there seems to be little room for a haptic equivalent of the "visual buffer," where quasi-pictures are manipulated. Such a buffer in the tactile modality should process different stimulus properties, compared to its visual equivalent. In fact, research on haptic and tactile processing has shown that our knowledge regarding external objects and their spatial relations acquired via the sense of touch is mediated by different sources of information, including pressure and temperature sensations, proprioception, and motor feedback (e.g., Davidson 1972; Lederman and Klatzky 1990; Voisin et al. 2002). Any theory of haptic mental imagery would then certainly need to incorporate this important observation. Moreover, in order to define a comprehensive theory of tactile imagery, one also needs to consider those differences between touch and vision that are relevant to the functioning of an imagery system. These might include capacity of the short-term memory buffer, accuracy of long-term representations, and limitations of tactile awareness. Any difference between sensory modalities regarding these aspects is likely to affect our ability to generate and maintain mental images.

3.4.1   Tactile and Haptic Short-Term Memory

Research on tactile memory has demonstrated that there is a "tactile buffer" where information is retained for short periods of time (see Gallace and Spence 2008a, 2009, 2010, for reviews). In particular, Bliss et al. (1966) investigated the ability of participants to report the locations of multiple tactile stimuli presented simultaneously

on the fingertips. They found evidence for the presence of a tactile sensory storage system of brief duration (i.e., approximately 0.8 s) and of large storage capacity. Note, however, that Bliss and his colleagues also reported that this temporary storage system had less capacity than the equivalent visual storage system. Interestingly, Gallace et al. (2008a, b) recently reported that the temporal limitations of tactile short-term memory systems might be a function of the amount of stimuli presented in the display (and/or of their complexity). Taken together, the results of the studies regarding tactile short-term memory in sighted individuals performed so far would seem to suggest the presence of more severe limitations than those observed in visual studies. That is, memory representations for simple stimuli presented across the body surface seem to be of shorter duration and have less capacity than visual representations. This is certainly a factor that might affect the ability of sighted individuals to operate on tactile mental images. However, whether this putative difference between short-term memory capacity of vision and touch can be solely (or mainly) related to the role of practice is still a question that needs to be more extensively addressed (e.g., Saito et al. 2007; see also Cornoldi et al. 1991, for a discussion on the individual differences in visuo-spatial short-term memory of blind and sighted participants).

As far as "haptic" short-term memory is considered, the results of a number of studies by Kiphart and his colleagues (1988) on 304 sighted participants showed no evidence of a short-term memory decay for haptically explored complex tridimensional objects, over retention intervals that ranged from 0 to 80 s (see also Craddock and Lawson 2010). On the basis of these results, the authors suggested that people's capacity to retain information of a haptic nature is somehow superior to that observed for vision and audition and that this might be due to the fact that the haptic modality is not limited to a single sense organ or receptor but is, in fact, a composite of several interrelated mechanisms. That is, following on from these considerations, one might expect that haptic mental imagery, by relying on more stable representations, is superior to tactile mental imagery and even to visual mental imagery. The fact that such a difference has never been reported so far should be taken to suggest that more than one factor is likely to affect people's ability to generate and hold mental images of haptically explored stimuli.

3.4.2 Tactile and Haptic Long-Term Memory

One relevant aspect of Kosslyn's theory of visual imagery is that the potential mental images are initially stored as "deep representations" in long-term memory. While a few studies have investigated short-term memory for tactile stimuli, very little research has studied long-term tactile memory. The few studies that have addressed this topic investigated the ability of people to recognize objects via the sense of touch (e.g., Klatzky et al. 1985; Kilgour and Lederman 2002). In order to perform this task, participants need to know how different objects feel to the tactile sense. Therefore, access to long-term tactile memory is likely required (e.g., Klatzky et al. 1985;

Heller et al. 1996; Lederman et al. 1990; Magee and Kennedy 1980). However, while haptic identification of familiar objects is both rapid (less than 2 s) and accurate (less than 5% error rate) (Klatzky et al. 1985), performance with other stimuli can be very variable (see Lawson and Bracken 2011, for a review). These results would seem to suggest that tactile and haptic deep representations might suffer from more severe limitations than their visual equivalent. Note, however, that the possibility that stimuli can be stored within long-term representations using multisensory rather than unisensory codes (e.g., Lacey et al. 2009) and that the sensory modality that retains more information might change as a function of the use of that information should be considered. That is, for certain objects, visual qualities might be more important than tactile qualities, and as a consequence, more of this information may be retained in our long-term memory system. The opposite might occur for other stimuli (e.g., in order for a doctor to correctly recognize a swollen gland, visual information might be not as relevant as tactile information). As a consequence, information stored in a long-term memory task might strongly affect the participant's performance and the estimation of the limitations of the retained representations. Following on from these considerations, one should expect that people's ability to build and retain tactile and haptic mental images should be affected by the nature and characteristics of the stimuli to be imagined. Moreover, considering that mental images regarding our sense of touch are built upon long-term representations, further studies should be addressed at investigating the contents of these representations. That is, to what extent proprioceptive, thermal, and pressure sensations contribute to our deep representations? And to what extent they can be utilized in order to build tactile and haptic mental imagery?

3.4.3 Consciousness of Tactile Stimuli

A further important point in Kosslyn's theory of visual imagery is that while deep representations are not directly accessible to awareness, information contained in the visual buffer is. This claim implies that any possible difference in access to awareness of visual and tactile information might be relevant to the functioning of mental imagery. The question of whether visual and tactile awareness have similar characteristics and, even more specifically, similar limitations and capacities becomes therefore relevant.

A large body of research in the past century has been dedicated to the question of the amount of stimuli that can enter our awareness at any one time (e.g., Atkinson et al. 1976; Jevons 1871; Glanville and Dallenbach 1929; Mandler and Shebo 1982; Peterson and Simon 2000; Trick and Pylyshyn 1994). In particular, many studies on visual numerosity judgments (where participants are required to count the number of stimuli presented simultaneously in a display) have shown that up to 4 stimuli can be processed very rapidly and near-perfectly (e.g., Atkinson et al. 1976). This number has often been claimed to constitute the putative limit of the human capacity of perceiving events at any one time or the "span of our consciousness" (see Jevons 1871;

see also Atkinson et al. 1976; Peterson and Simon 2000). More recently, a few studies have begun to investigate this topic for other sensory modalities (e.g., Gallace et al. 2006, 2007a, 2008a, b; Ferrand et al. 2010; Plaisier et al. 2009; Riggs et al. 2006). Gallace and his colleagues (2006; 2007a) tested people's ability to count simultaneously presented tactile stimuli distributed on the fingertips or across the body surface. On the basis of their results, they claimed that humans are aware of no more than two tactile stimuli presented on a given location at any one time (though see Riggs et al. 2006). That is, on the basis of Gallace et al.'s results, one might conclude that the span of consciousness for the tactile modality is more limited than its visual equivalent (at least when the stimuli are presented simultaneously). This limitation certainly needs to be considered when studying tactile mental imagery and might be taken to suggest that people can retain and form less complex tactile than visual mental images.

In summary, the evidence reported so far would seem to suggest that whenever similar procedures are adopted in order to understand the functioning of the visual and tactile information processing systems, important differences between the two sensory modalities do arise. All of the functions that, on the basis of Kosslyn's (1980, 1994) model, are thought to support mental imagery (e.g., short- and long-term memory and awareness of information) would seem to suffer from different limitations between the senses. More precisely, the tactile modality often has more limitations than the visual modality (e.g., Bliss et al. 1966; Heller et al. 1996; Lederman et al. 1990; Magee and Kennedy 1980; Gallace et al. 2006; 2008a, b). These limitations are likely to affect the ability to generate mental images on the basis of tactile and haptic information.

3.5 The Role of Vision in Tactile Mental Imagery

One of the most relevant problems of studying tactile mental imagery is to prevent visual imagery being used instead. Sighted individuals are certainly more accustomed to make mental transformations on visual images than on their tactile equivalent and tend to have concomitant visual imagery and visual cortex activation during tactile imagery tasks (e.g., Uhl et al. 1994). One of the ways of solving this problem is to test visually impaired individuals, who cannot adopt visual strategies. However, this approach also precludes studying tactile imagery in the sighted population where adaptation to the lack of visual input is not an issue (see Lambert et al. 2004, for the report of activation of the visual cortex in early blind participants during mental imaging tasks). Alternatively, tactile mental imagery in sighted individuals might be studied by using procedures that prevent the participants from using visual strategies. In fact, studies of haptic and tactile information processing have shown that tactile object recognition is decreased following visual interference (e.g., Holtby and D'Angiulli 2012; see also Lacey and Campbell 2006, for similar results in a crossmodal memory task). This result has been taken to suggest that tactile representations of objects might be retained by means of multisensory rather than

unisensory codes and that tactile mental imaging in sighted individuals can be mediated by multisensory rather than unisensory processing (see Lacey et al. 2011; Lacey and Sathian 2011 on this point). Unfortunately, using visual interference to study haptic and tactile imagery in sighted individuals has been rarely explored by researchers. This apparent scarcity of research on this topic might be related to the fact that visual interference procedures not only prevent the generation of visual images but also limit the amount of cognitive resources available for performing the task. That is, the study of tactile mental imagery under these conditions of stimulus presentation requires accurate paradigms in order to avoid the influence of confounding factors.

Another way of investigating the role of vision in tactile imagery is by considering individual differences in mental imagery. Research on visual imagery has shown that people differ in their ability to generate and manipulate mental images (e.g., Marks 1973; see also Kozhevnikov et al. 2002; 2005). That is, if there is no difference between high and low ability visual imagers on a tactile mental imaging task, one might reasonably conclude that visual information does not affect their performance. For example, in a study by Kilgour and Lederman (2002), a group of blindfolded participants were asked to identify with their hands a standard face from among three comparison faces (i.e., two distractors and one target). They found that the participants' accuracy in this task exceeded 80% correct (where chance was 33% correct; see also James et al. 2006; Kilgour et al. 2004, for similar results). Interestingly, Kilgour and Lederman (2002) also reported that there was no correlation between the ability of their participants to use visual imagery (as assessed by means of the Vividness of Visual Imagery Questionnaire, VVIQ; Marks 1973) and their accuracy or response time. On the basis of this result, they concluded that the haptic representation and recognition of human faces were not necessarily mediated by visual information. Note, however, that in this case, tactile recognition rather than tactile imagery was investigated.

3.5.1 Tactile Imagery and Synesthesia

An additional possibility for studying the relationship between tactile mental imaging and visual processing is related to the capability of visual information to elicit tactile images. For example, the sight of the Laocoön Group, in the Vatican Museum of Rome, might make a person somehow shiver as if the snakes were wrapped around his or her skin (see Gallace 2011; Gallace and Spence 2011). That is, to what extent can vision provoke tactile images? A large body of research evidence has shown that sensations in one sensory modality can be elicited by stimuli presented from a different sensory modality, a phenomenon known as "synesthesia" (e.g., Baron-Cohen and Harrison 1997; Cytowic 2002; Cytowic and Eagleman 2009). Research has also shown that visual, auditory, and tactile stimuli are all effective in triggering these synesthetic sensations. For example, Blakemore et al. (2005) described the case of a woman who, following the observation of another person

being touched, experienced the presence of tactile stimulation on the equivalent part
of her own body (a visuotactile form of synesthesia named "mirror-touch synesthe-
sia"; e.g., Banissy and Ward 2007).

Interestingly, Blakemore and her colleagues (2005) by using fMRI also mea-
sured the brain activity of their synesthetic subject and of a group of non-synesthetic
individuals, during the observation of touch to different parts of another body or of
an object. They found that the somatosensory cortex (an area of the brain responsi-
ble for the processing of tactile information), the premotor, and parietal cortices
were activated both in the non-synesthetic participants and in the synesthetic patient
during the observation of touch. Interestingly, however, no actual tactile experiences
were reported by non-synesthetic participants. That is, while tactile sensations can
be elicited in synesthetic individuals by means of visual stimuli, similar procedures
and similar brain activations do not elicit the same effects in non-synesthetic indi-
viduals. In the case of the patient studied by Blakemore and her colleagues, tactile
representations were likely activated by means of visual information; however, no
further investigation was conducted on the characteristics of these representations.
Can these representations be retained also when the visual stimulus is removed and
can they be manipulated over time? If one's aim is to understand the mechanisms
behind tactile mental imagery and their possible links with synesthetic phenomena,
these questions certainly need to be addressed.

3.6   Mental Imagery and Hallucinations

Hallucinations may be considered "sensory experiences that occur in the absence
of external stimulation of the relevant sensory organ, have the compelling sense of
reality of a true perception, are not amenable to direct and voluntary control by the
experiencer, and occur in an awake state" (Aleman and De Haan 1998; see also
Slade and Bentall 1988). A large body of literature in the last century has considered
hallucinations as phenomena strongly related to mental imagery. In particular, it has
often been claimed that an erroneous attribution of internally generated events to
external sources may result from mental images having more perceptual character-
istics than expected by the cognitive system (e.g., Barrett 1992; Mintz and Alpert
1972; Roman and Landis 1945; Slade 1976; see Aleman et al. 2000, for a discussion
on this point). That is, mental imagery resembles hallucination in that mental images
also have perceptual qualities and occur in the absence of the appropriate external
stimulus. Given this important similarity, the study of hallucinations should be con-
sidered relevant to the study of mental imagery (and more in general of perception;
see Gibson 1970, on this point). The question to be answered here then becomes:
Are people able to hallucinate tactile content?

Little research has been conducted on the topic of tactile hallucinations, as com-
pared to the much larger body of research dedicated to visual forms of hallucina-
tions (e.g., Bressloff et al. 2001; Kluver 1966). However, many cases of tactile
hallucinations, following brain injury, dementia, hypophyseal tumor, diabetes, and

different psychosis, have been reported (see also Gallace and Spence 2010). These hallucinations include itches (Darwin 1796), formication (i.e., an abnormal sensation like insects crawling upon the skin; cf. Caporael 1976; Matossian 1982), pinching, rubbing (Regis 1906), and having the skin covered in fur (Storring 1907). Interestingly, there are also reports of more complex tactile hallucinations, such as the sensation of being kissed, of having someone lying by one's side, and even of sexual experiences (Kraepelin 1919; see also Berrios 1982). It is important to note here that the more complex the hallucination, the more likely it is multisensory. For example, a particularly well-known form of hallucination, named "delusional parasitosis" (e.g., Huber et al. 2008; Musalek et al. 1989; see de Leon et al. 1992, for a review on this syndrome), is characterized by the conviction that small creatures are infesting one's skin and includes both visual and tactile sensations.

   Unfortunately, there are no studies that have directly compared the amount of tactile and visual hallucinations reported by patients. As a consequence, one might wonder whether the relative paucity of tactile hallucinations reported in the literature is related more to a visually oriented preference of researchers, rather than to a more limited ability of the tactile system to generate images without an actual counterpart in the external world. What instead would seem to emerge more clearly from the reports summarized here is that complex hallucinations in touch are usually accompanied by multisensory (visual and/or auditory) sensations and that complex, purely tactile, hallucinations are less common.

3.7   Tactile Images of the Body

We now know that the sense of touch is strongly related to the way in which we represent our body (e.g., Moseley et al. 2012; Gallace and Spence 2008b, 2010). Tactile receptors are distributed across the body surface, and the sensations from them help to differentiate our body from the external world. That is, whenever we touch an object, we can perceive two different, but related, signals: one that informs us of the external stimulus and one that informs us of the presence of our body in space. Research in the last decade has convincingly demonstrated that tactile stimulation can be attributed to external/artificial objects and that this phenomenon has important consequences on our sense of body ownership (e.g., Botvinick and Cohen 1998; see Makin et al. 2008; Moseley et al. 2012, for recent reviews). These observations clearly suggest that our ability to generate and manipulate tactile images may be influenced by our body representation. In fact, it has been suggested that we maintain at least two different representations of our body in our brain, a "body image" and a "body schema" (Head and Holmes 1911). The term "body image" is typically used to refer to a conscious visual representation of the way that the body appears from the outside when viewed in a canonical posture (e.g., Haggard and Wolpert 2005; Head and Holmes 1911). By contrast, the "body schema" refers to a postural model that is continuously modified and updated whenever we move or adopt a new posture (e.g., Head and Holmes 1911;

see also Haggard et al. 2006). The latter representation is somehow dissimilar from mental images in that while mental images are generally created and manipulated for a given task, the body schema is an internal and "permanent" (though modifiable) representation used for moving and locating our body in space (see Moseley et al. 2012).

As far as images of the body are concerned, one might wonder about whether (and to what extent) people can create or modify a *temporary* mental image of their body. In the classic rubber hand illusion, synchronous stroking of a participant's unseen real hand and a seen artificial hand induces the sensation that the artificial hand is actually part of the person's own body (Botvinick and Cohen 1998). In this paradigm, visual information regarding the artificial body part (e.g., the rubber hand) is constantly provided in order to elicit the illusion; therefore, the creation of a visual mental image of the new body (or of a part of it) is unlikely. However, illusions of body ownership induced by means of the rubber hand procedures have been reported without providing visual information to the participants (Ehrsson et al. 2005). In those cases, proprioceptive and tactile information sufficed to elicit the illusion. Unfortunately, however, also in this case, we do not know what really occurs to our body image while experiencing the illusion. Is a visual or tactile mental image of the body temporarily created and modified? Moreover, we know that proprioceptive information is likely to play a major role in supporting a mental image of the body, but do not fully know what the role of tactile information is in this task, especially when the image needs to be manipulated.

Only one study has directly addressed the question related to the presence of tactile images of the body. Keizer et al. (2011) investigated alterations of tactile body image in anorexia nervosa. Not surprisingly, the literature on body image in anorexia nervosa has focused mainly on attitudinal (e.g., body dissatisfaction) and visual aspects of body image (Smeets 1997; Smeets et al. 1997; Skrzypek et al. 2001), while little is known about somatosensory aspects. Keizer and her colleagues measured tactile body image by presenting two tactile stimuli to the forearm and abdomen of their blindfolded participants. They also asked their participants to estimate the distance between the two tactile stimuli. The results showed that patients affected by anorexia nervosa not only visualized their body less accurately (e.g., larger than it really was; consistently with previous literature) but also overestimated distances between tactile stimuli. That is, tactile as well as visual body image was altered in this group of participants suggesting that tactile images of the body can be generated and that they can be altered, especially in patients affected by certain disorders. However, the question of whether tactile images of the body can be generated and manipulated at any one time or within relatively short amounts of time (i.e., not necessarily as a consequence of a prolonged pathological condition) remains unanswered. This is another important topic that future research will need to address.

3.8 An Imagery for Pain?

The question of whether or not pain and touch should be considered separate sensory modalities is still a matter of debate among philosophers and researchers (see Weber 1834/1978 for the definition of "coenesthesis of the skin" as the sense by which we perceive pain; see Auvray et al. 2010, for a discussion on this point). Despite this observation, pain is certainly important for our representations of the stimuli presented on our body. An extensive (although controversial) amount of literature has been published on the use of mental imagery to ease pain (e.g., McCaffrey and Beebe 1989; Moran 1989; Pearson 1987), and the use of imagery has even been recommended as an adjunctive or complementary therapy to traditional analgesic regimens to maximize pain relief (Agency for Health Care Policy and Research 1994).

A number of studies have shown that visuo-motor imaging can be effective in reducing phantom limb pain in amputees (e.g., MacIver et al. 2008; though see Chan et al. 2007; see also Moseley et al. 2008). However, as far as purely noxious mental imaging is concerned, no study has ever addressed whether we can create and manipulate painful mental images. This is certainly not surprising, considering that pain is something that people generally want to get rid of, rather than to be reminded of. However, just as research on visual imagery has highlighted some important aspects of the functioning of our visual system, research on pain imagery might provide some interesting insights into, for example, whether imaging of pain can increase or decrease our actual feelings of pain. Other important questions to be answered here relate to whether we are actually able to create "images" of pain and, if not, why are we able to create mental images within certain sensory modalities and not in others.

Among clinicians, mental imagery, generally visual or visuo-motor, is used as a treatment for pain (e.g., McCaffrey and Beebe 1989; Moran 1989; Pearson 1987). Within this therapeutic approach, patients (generally suffering from chronic forms of pain) are asked to relax and try to generate a given mental image while experiencing their pain. A typical use of mental images for the treatment of painful conditions relates to patients affected by phantom limb pain or chronic regional pain syndrome (e.g., Moseley 2004, 2006; Brodie et al. 2007). In these cases, asking the patients to create mental images of their affected body part (being it the phantom or the painful limb) and to move it in space often results in temporary pain relief (note however that this treatment method in order to be effective generally needs to be part of a more complex set of procedures; see Moseley et al. 2012). An alternative approach involves the patient generating an image of their pain and then performing modifications of this image, while in a relaxed or hypnotic state (e.g., Alexander 1971; Pincus and Sheikh 2009). However, this procedure focuses more on the effects of creating and modifying mental images related to pain, than on the content of the images itself. Moreover, this approach does not assess whether patients affected by chronic pain can create and modify images of pain outside the therapeutic session.

Few studies have investigated spontaneous mental imagery linked to pain symptomatology (e.g., Carruthers et al. 2009; Chaves and Brown 1987). However, also in this case, although the results suggest that patients can generate and report a mental image of their pain, the nature (visual, verbal, or noxious) of this imagery remains unclear. A recent study has more directly investigated the presence and the content of spontaneous mental images of pain in patients suffering from chronic pelvic pain (Berna et al. 2011). By using questionnaire procedures, the authors found that all of their patients reported negatively valenced mental images related to their pain. Some of these spontaneously generated images were related to visual experiences associated with pain (e.g., "Bright operating room lights"), but others were more directly related to pain and somatosensory sensations (e.g., "A little man jumping on my lower abdomen. He is the pain"; "There's a heavy, grey lead ball where it hurts. The weight is surprising, given its size." "It's dragging down, as if it was going to fall out of me, taking my insides out").

In summary, the little clinical research performed to date clearly shows that mental images about pain of both negative and positive valence can be created within a therapeutic setting but also spontaneously by the patients. Pain-related mental images seem to be multisensory including visual, acoustic (e.g., "My children are crying"; see Berna et al. 2011), and tactile sensations. The question of whether or not purely "noxious" mental images can be created remains unanswered. Future studies will need to address this important topic by using not only pencil and paper questionnaires but also standard experimental procedures.

3.8.1 Mental Images of Pain and Synesthesia

Few studies have investigated pain and mental images in the healthy population. This research has mainly investigated whether visual images of pain can elicit painful sensations in the observer: Can seeing somebody else in pain actually cause pain? In a recent study, Osborn and Stuart (2010) presented healthy participants with a series of images or short video clips depicting noxious events (such as a person receiving an injection or breaking a leg). Then, the participants had to report if they felt any pain as a consequence of watching the image. The pain was rated using an analogue visual scale and the short-form McGill Pain Questionnaire (see Melzack 1975). Nearly one-third of the participants reported an actual noxious experience as a consequence of watching the images (a sort of mirror synesthesia of pain). These participants also showed higher level of brain activation (measured by using fMRI) in areas of their brain involved in pain processing during the observation of pain.

Synesthesia for pain has also been described in amputees with phantom limb pain (e.g., Giummarra and Bradshaw 2008; Giummarra et al. 2010; see also Fitzgibbon et al. 2010) in a man with hyperalgesia and lung cancer (e.g., Bradshaw and Mattingley 2001) and in a woman following a traumatic labor (e.g., Giummarra and Bradshaw 2008). It is important to highlight here that participants in the great majority of the studies reported in this section were not directly required to imagine pain, but rather, they had to watch other people in pain. That is, even if the effects

reported were mediated by imaging rather than by watching pain, the visual modality would appear to be always involved in the perceived experience of pain. As a consequence, whether or not the phenomena described here can be also mediated by mental imagery of pain is not known.

3.9 Conclusions

The literature reviewed in this chapter has clearly shown that sighted as well as visually impaired individuals can generate and manipulate images based on somatosensory information, just as they can for visual images (e.g., Cornoldi et al. 1979; Uhl et al. 1994; see Kosslyn 1980, 1994). However, our review of the literature has also highlighted important aspects of tactile imagery that will need to be further addressed by future research. For example, we do not know the role of proprioception, thermic, and noxious sensations in tactile imaging or the link between tactile imaging and tactile hallucinations or certain forms of visuotactile synesthesia. Different sensory modalities might differ in their ability to sustain mental imagery. These differences might be related to different parameters, such as the amount of the neocortex that is given over to the processing of each sense (cf. Felleman and van Essen 1991) or with the bandwidth of each sensory modality (i.e., the quantity and quality of information that a given sensory system can analyze; e.g., Desor and Beauchamp 1974; Miller 1956; Questler 1955; Zimmerman 1989). The usefulness of these parameters is sometimes debatable (see Gallace et al. 2011), but on the basis of them, touch should suffer from the most severe limitations in mental imagery capabilities (at least when compared to vision and audition). As far as painful sensations are concerned, the literature on synesthesia, as well as that on patients suffering from chronic pain, would seem to suggest that pain imaging is multisensory in nature (e.g., Legrain et al. 2011; see also Moseley et al. 2012).

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Chapter 4
Auditory Aspects of Auditory Imagery

Timothy L. Hubbard

Abstract Empirical findings from studies on imagery of auditory features (pitch, timbre, loudness, duration, tempo, rhythm) and imagery of auditory objects (musical contour and melody, musical key and harmony, notational audiation, speech and text, environmental stimuli) are reviewed. Potential individual differences in auditory imagery (involving vividness, auditory hallucination, development, musical ability, training) are considered. It is concluded that auditory imagery (a) preserves many of the structural and temporal properties of auditory information present in auditory (or multisensory or crossmodal) stimuli, (b) can impact subsequent responding by influencing perception or by influencing expectancies regarding subsequent stimuli, (c) involves mechanisms similar to many of those used in auditory perception, and (d) is subserved by many of the same cortical structures as is auditory perception.

Keywords Auditory imagery • Music • Speech • Reading • Auditory perception • Individual differences • Auditory features • Objects

4.1 Introduction

Research on auditory imagery has often involved examination of how information regarding auditory features and auditory objects is preserved in imagery and how this information influences other cognitive processes. This research is reviewed, and

T.L. Hubbard (✉)
Department of Psychology, Texas Christian University,
Fort Worth, TX 76132, USA
e-mail: timothyleehubbard@gmail.com

some general properties of auditory imagery are suggested. The focus is on auditory components of auditory imagery (discussion of multisensory and crossmodal components can be found in Chap. 12). Individual differences in auditory imagery that involve the vividness of auditory imagery, relationship of auditory imagery to auditory hallucinations, development of auditory imagery, and relationship of auditory imagery to musical ability and training are considered. For the purposes here, auditory imagery is defined as an introspective and nonhallucinatory experience of auditory sensory qualities in the absence of a corresponding auditory stimulus (cf. Baddeley and Logie 1992; Intons-Peterson 1992; Kosslyn et al. 1995). Imagery of auditory features and auditory objects is considered in Sects. 4.2 and 4.3, respectively, and individual differences in auditory imagery are considered in Sect. 4.4. Suggestions regarding properties of auditory imagery are presented in Sect. 4.5, and some conclusions are given in Sect. 4.6.

4.2 Auditory Features

Most discussions of auditory features involve structural or temporal properties of an auditory stimulus (e.g., wavelength, amplitude, stress pattern). Accordingly, auditory features considered here include pitch, timbre, loudness, duration, and tempo and rhythm.

4.2.1 Pitch

Farah and Smith (1983) had participants listen to or image tones of 715 or 1,000 Hz and simultaneously or subsequently detect whether a target tone of 715 or 1,000 Hz was presented. Imaging the same, rather than a different, frequency facilitated detection if detection was simultaneous with, or subsequent to, image generation. Hubbard and Stoeckig (1988) had participants image a single tone that varied across trials, and after participants indicated they had an image, a target tone was presented. Participants judged whether the pitch of the target tone was the same as or different from the pitch of the imaged tone. Judgments were facilitated if the pitch of the image matched the pitch of the target. Okada and Matsuoka (1992) had participants image a tone of 800 Hz and then discriminate which of five target tones was presented. Discrimination was poorer if the pitch of the image matched the pitch of the tone, and this seemed inconsistent with findings of Farah and Smith and of Hubbard and Stoeckig. Okada and Matsuoka suggested the difference between their findings and those of Farah and Smith reflected the difference between detection and discrimination (cf. Finke 1986); however, it is not clear if the same applies to the difference between their findings and those of Hubbard and Stoeckig.

Halpern (1989) had participants indicate the first pitch of a well-known melody (e.g., *Somewhere Over The Rainbow*) by humming or by pressing a key (located by touch on a visually occluded keyboard). Participants generally chose lower or higher starting pitches for melodies that ascended or descended, respectively, in pitch during the first few notes. The same participants were subsequently presented with their previously indicated starting pitch (not identified as such) and other possible starting pitches, and they generally preferred their previously indicated pitch or a pitch a specific musical interval from their previously indicated pitch. Halpern suggested this was consistent with a form of absolute pitch in memory for the starting note (cf. Schellenberg and Trehub 2003). Intons-Peterson et al. (1992) examined relative pitches of different pairs of stimuli. Verbal descriptions of common objects (e.g., cat purring, door slamming) were visually presented, and participants formed auditory images of the sounds indicated by those descriptions. If participants judged whether the pitch of the first sound was the same as the pitch of the second sound, then response times decreased with increases in pitch distance. If participants adjusted the pitch of one sound to match the pitch of the other sound, then response times increased with increases in pitch distance.

Janata (2001) examined emitted potentials related to auditory imagery. Participants listened to the initial portion of an ascending or descending instrumental phrase and then imaged a continuation of that phrase. In some conditions, subsequent expected notes were not presented, and participants exhibited an emitted potential similar to the evoked potentials for perceived pitches. Janata and Paroo (2006; Cebrian and Janata 2010b) presented participants with the first few notes of a scale and participants imaged the remaining notes. The final note was presented, and participants judged whether that note was in tune. Judgments were not influenced by whether participants listened to all of the notes or imaged some of the notes, and Janata and Paroo concluded participants had a high level of pitch acuity. Pecenka and Keller (2009) found that auditory images of pitch were more likely to be mistuned upward than downward. Cebrian and Janata (2010a) reported that, for participants with more accurate images, the amplitude of the N1 in response to a target tone after a series of imaged pitches was smaller and comparable to the N1 if the preceding pitches had been perceived. The P3a response to mistuned targets was larger for participants who formed more accurate auditory images. Also, auditory images were more accurate for pitches more closely associated with the tonal context than for pitches that were less closely associated (cf. Vuvan and Schmuckler 2011).

Numerous studies suggest representation of perceived pitch involves a vertical dimension (e.g., Eitan and Granot 2006; Spence 2011), and Elkin and Leuthold (2011) examined whether representation of imaged pitch similarly involved a vertical dimension. Participants compared the pitch of a perceived tone or an imaged tone with the pitch of a perceived comparison tone, and the response keys were oriented horizontally or vertically. Whether a pitch should be imaged at 1,000, 1,500, or 2,000 Hz was cued by visual presentation of the letters A, B, or C, respectively. For imagery and for perception, judgments of tones closer in pitch yielded

longer response times and higher error rates than did judgments of tones more distant in pitch (cf. Intons-Peterson et al. 1992). Also, responses were faster if lower-pitched imaged tones involved a bottom-key or left-key response and higher-pitched imaged tones involved a top-key or right-key response, and Elkin and Leuthold suggested tones were coded spatially (cf. Keller et al. 2010; Keller and Koch 2008). Such a pattern is consistent with the SMARC (spatial-musical association of response codes) effect in perceived pitch (e.g., see Rusconi et al. 2006) and with the hypothesis that imaged pitch involves the same properties as perceived pitch.

4.2.2   Timbre

Crowder (1989) presented a sine wave tone and instructed participants to image that tone in the timbre of a specific musical instrument (e.g., flute, guitar, piano). Participants judged whether the pitch of a subsequently perceived tone matched the pitch of the image; response times were faster if the subsequent tone was in the timbre participants had been instructed to image. Pitt and Crowder (1992; Crowder and Pitt 1992) found spectral elements of imaged timbre, but not dynamic elements of imaged timbre, influenced response times to judgments of subsequently presented tones. Halpern et al. (2004) had participants rate similarities of pairs of musical instrument timbres. Ratings of imaged timbres were highly correlated with ratings of perceived timbres. Timbre perception activated primary and secondary auditory cortex, but timbre imagery only activated secondary auditory cortex. Timbre imagery and perception activated superior temporal area, and timbre imagery also activated supplementary motor cortex. Bailes (2007) had music students judge whether timbre of a perceived probe note differed from timbre of a target note in a perceived, imaged, or controlled musical context. Participants' images appeared to represent timbre, but timbre information was not always explicitly available (see Halpern 2007).

4.2.3   Loudness

Intons-Peterson (1980) visually presented pairs of verbal descriptions of common environmental sounds (e.g., police siren, thunder), and participants formed auditory images of the sounds indicated by those descriptions. The time required to generate an image was not related to ratings of the loudness of the described sound. If participants formed images of two sounds and then adjusted imaged loudness of one sound to match imaged loudness of the other sound, response time increased with increases in the initial difference in imaged loudness (cf. Mannering and Taylor 2008–2009). Pitt and Crowder (1992; Crowder and Pitt 1992) had participants form an image of a tone that was subjectively either soft or loud. Participants judged

whether a subsequently presented probe tone was the same pitch as the image. The probe tone was soft or loud, and response time was not influenced by whether loudness of the probe tone matched loudness of the image. Intons-Peterson (1980) and Pitt and Crowder (1992) suggested loudness was not necessarily specified in an auditory image (cf. Wu et al. 2011). Curiously, Pitt and Crowder did not examine whether loudness in an image primed judgment of loudness of a subsequent percept, but such a comparison would have offered a more direct examination of whether loudness information was specified within an auditory image.

Wu et al. (2010) had participants learn associations between visual shapes and auditory tones that differed either in pitch or loudness. Participants were then presented with a shape and imaged a tone of either a constant loudness at the indicated pitch or a constant pitch at the indicated loudness. Participants then judged whether their imaged tone matched a subsequently perceived tone. If there was a mismatch between the pitch or loudness of the imaged tone and that of the perceived tone, an N2 was elicited, and amplitude of the N2 increased if there was a larger discrepancy between the imaged and perceived tones. Wu et al. (2011) presented similar stimuli, and they found amplitude of the late positive component (LPC) decreased with decreases in imaged pitch but increased with increases in imaged loudness. Similarly, amplitude of the N1 decreased with decreases in perceived pitch but increased with increases in perceived loudness. The similarity in LPC in imagery and N1 in perception led Wu et al. (2011) to conclude that auditory imagery encoded loudness and pitch information, but this conclusion seems inconsistent with Intons-Peterson's (1980) conclusion that loudness information is not necessarily present in auditory images.

4.2.4 Duration

Halpern (1988a; also Aleman et al. 2000; Zatorre and Halpern 1993; Zatorre et al. 1996) presented participants with two written lyrics from a well-known melody (e.g., *Hark the Herald Angels Sing*), and participants were instructed to begin on the first lyric and "mentally play" through the melody until they reached the second lyric. Response time increased with increases in the distance (i.e., the number of beats) between the two lyrics. Nees and Walker (2011) instructed participants to encode a sequence of tones as either a verbal list, visuospatial image, or auditory image. Subsequent scanning time of encoded information was closest to the original duration of the tone sequence for auditory images. Weber and Bach (1969; Weber and Castleman 1970) reported speech imagery and speech recitation for letters of the alphabet required approximately equal durations, but Aziz-Zadeh et al. (2005) reported that speech imagery was faster than actual speech and also required more time for speech stimuli containing more syllables. Janata and Paroo (2006) measured temporal acuity regarding when participants expected the final note of a scale to occur; they found temporal acuity was less than pitch acuity and was more susceptible to distortion in the absence of an external stimulus.

4.2.5 Tempo and Rhythm

Halpern (1988b) had participants adjust the tempo on a metronome to match the imaged or perceived tempo of a familiar song. Tempo settings varied across melodies, and tempo settings for imaged and perceived versions of the same melody were highly correlated. Halpern (1992) found that participants with musical training exhibited greater flexibility in the range of tempi at which they could image a familiar melody and greater stability of imaged tempi for a given melody across sessions. Vlek et al. (2011) had participants perceive or image different metric patterns in which the first beat of a two, three, or four note isochronous sequence was accented. Imaged accents were superimposed upon the ticking of a metronome, and EEG was acquired. A time window of 500 ms around each metronome click was selected, and EEG was averaged across these windows. Accented beats resulted in larger positive amplitude than did unaccented beats after 180 or 200 ms for perception or imagery, respectively, and accented beats resulted in a larger negative amplitude than did unaccented beats after 350 ms for perception and imagery. Vlek et al. concluded it was possible to distinguish accented and unaccented beats within the EEG and that there were shared mechanisms for perception and imagery.

4.3 Auditory Objects

Most sounds are not perceived as independent or isolated features, but are perceptually grouped with other features to form meaningful objects. The auditory objects considered here include musical contour and melody, musical key and harmony, notational audiation, speech and text, and environmental objects.

4.3.1 Musical Contour and Melody

Weber and Brown (1986) had participants draw horizontal lines reflecting pitch height of notes in imaged or perceived melodies. Responses for imagery and for perception of each melody were highly correlated, and error rates and response times were not influenced by whether a melody was imaged or perceived. Zatorre and Halpern (1993) presented participants with two written lyrics from a well-known melody. Participants then imaged or listened to the melody, and they judged which lyric was sung on the higher pitch. Participants with a right temporal lobe lesion performed worse than participants with a left temporal lobe lesion or control participants. Zatorre et al. (1996) acquired PET during a similar pitch comparison task and found activation in superior temporal gyrus and areas of frontal and parietal lobe during perception and imagery; additionally, supplementary motor area, areas of the thalamus, and frontal areas were activated during imagery. To examine

whether activation of supplementary motor area was due to vocalizable lyrics, Halpern and Zatorre (1999) acquired PET from participants who imaged instrumental music and found activation in right superior temporal gyrus, right frontal lobe, and supplementary motor area even in the absence of vocalizable lyrics. Halpern (2003) suggested this latter pattern reflected musical semantic memory rather than working memory.

In Halpern (1988a; also Aleman et al. 2005; Halpern and Zatorre 1999; Zatorre et al. 1996; Zatorre and Halpern 1993), participants scanned melodies in normal temporal order, but in Zatorre et al. (2010), participants scanned melodies in reversed temporal order. In Zatorre et al. (2010), participants were given the name of or listened to the first few notes of a well-known melody (e.g., theme from *The Pink Panther*). They then heard a sequence of notes and judged whether it was an exact or inexact reversal of that melody. Participants reported using auditory imagery, and fMRI suggested increased activation in intraparietal sulcus, as well as increased activation in ventrolateral and dorsolateral frontal cortex and right auditory cortex (cf. reversal of letter strings in Rudner et al. 2005). Zatorre et al. suggested activation of intraparietal sulcus reflected amodal manipulation of information subserving computations involving transformation of sensory input and that their findings were consistent with activation of intraparietal sulcus during mental rotation of visual stimuli. Participants were faster in responding to inexact reversals than to exact reversals, and Zatorre et al. suggested that in inexact reversals participants stopped scanning as soon as they reached an incorrect note, but in exact reversals, participants scanned all the way through the melody.

Schaefer et al. (2009) acquired EEG while participants imaged or listened to melodies, and they attempted to decompose the EEG into components reflecting different characteristics or functions of the music (e.g., interval size, relative and absolute pitch level, relative and absolute duration, harmonic structure). Rhythmic aspects of melodies were more isolable than were pitch or melody-driven aspects, and most of the variability in the EEG was accounted for by the lowest rhythmic level. The decomposed parameters for imagery and perception were highly correlated. Schaefer et al. (2011) had participants alternate between imaging and listening to musical excerpts, and they acquired EEG during imagery and during perception. Occipital-parietal high-band synchronized alpha (11 Hz) occurred in both imagery and perception; alpha was higher during imagery than perception, and in some participants, alpha was stronger in the right hemisphere. A similar increase in alpha during perception of harmonic and complex nonharmonic tones, as well as a left-lateralized increase in alpha for pure tones, complex tones, and nonharmonic complex tones during imagery, was reported by van Dijk et al. (2010).

Kraemer et al. (2005) acquired fMRI from participants who listened to excerpts of familiar or unfamiliar music, and small sections of music were replaced with silent intervals. Participants reported auditory imagery of the missing music during silent intervals in familiar, but not unfamiliar, music, and there was greater activation in auditory association areas during silent intervals in familiar than in unfamiliar music (but see Zatorre and Halpern 2005). Leaver et al. (2009) found participants who listened to a familiar CD reported auditory imagery of the upcoming track, and

these reports were linked with increased activity in right superior frontal gyrus, presupplementary motor cortex, dorsal premotor cortex, and inferior frontal gyrus. Spontaneous auditory imagery in Kraemer et al. and Leaver et al. is consistent with Janata's (2001) finding that emitted potentials in imagery were similar to evoked potentials in perception. Leaver et al. also had participants learn pairs of novel melodies, and then form an image of the second member of the pair when they heard the first. Reports of increased vividness of imagery correlated with activity in right globus pallidus and left inferior ventral premotor cortex, and there was increased activity in basal ganglia and the cerebellum during learning of novel melodies.

Although generation and experience of auditory imagery is often deliberate and under voluntary control, findings of Kraemer et al. (2005), Leaver et al. (2009), and Janata (2001) suggest auditory imagery of melodies might be automatic or involuntary in some circumstances. A clinical condition in which musical imagery is involuntary and unwanted is referred to as *musical hallucinosis* (Griffiths 2000; for brief overview, see Hubbard 2010). A nonclinical condition in which involuntary musical imagery occurs has been referred to as an *earworm* (Levitin 2007) or a *perpetual music track* (Brown 2006). Beaman and Williams (2010) found that earworms tended to be of familiar music and that individuals who reported music was more important to them tended to have longer earworms and more difficulty controlling them. Halpern and Bartlett (2011) found that earworms were more likely to reflect music the individual was recently exposed to. Also, earworms were more likely to occur in the morning and to involve music containing lyrics. The duration of an earworm varied greatly, and earworms usually ended on their own or if the individual listened to other music or engaged in some other (distracting) activity. Purely verbal earworms were relatively uncommon.

4.3.2 Musical Key and Harmony

Hubbard and Stoeckig (1988) had participants form auditory images of major chords, and participants judged whether pitches of the imaged chord were the same as pitches of a subsequently perceived major chord. Accuracy rates and response times were related to the harmonic relationship of the imaged chord and perceived chord and were consistent with previous studies of perceptual harmonic priming. Accuracy rates and response times were not influenced by pitch distance (cf. Elkin and Leuthold 2011; Intons-Peterson et al. 1992), and this suggested imagery of chords activated musical schemata that overrode the effects of pitch distance. Meyer et al. (2007) had participants form images of major or minor chords, and image formation was time-locked to a visual stimulus. Generation of images of chords resulted in a N1 and a LPC; N1 was associated with activity in anterior temporal regions, and LPC was associated with activity in cingulate, medial frontal regions, and right auditory association cortex (cf. Wu et al. 2011). Vuvan and Schmuckler (2011) presented musically trained participants with a cue

tone, and participants then imaged a major scale or a minor scale based on that cue tone. A probe tone was presented, and participants rated how well that probe tone fit the context of the imaged scale. Ratings with imaged scales were consistent with previous studies in which participants rated how well a perceived probe fit the tonal context of a perceived scale.

4.3.3 Notational Audiation

Auditory imagery of music that is evoked by reading a music score is referred to as *notational audiation* (e.g., Gordon 1975). Waters et al. (1998) reported musicians could judge whether a perceived auditory sequence matched a visually presented musical score (see also Wöllner et al. 2003). Kalakoski (2007) presented participants with visual notes on a musical staff or with verbal names of notes (e.g., "A," "F-sharp," "D-flat"). Musicians recalled notes better than did nonmusicians if notes were on a musical staff but not if notes were verbally named, and Kalakosi suggested this reflected musicians' experience of auditory imagery of the music when reading a score. Schürmann et al. (2002) acquired magnetoencephalography (MEG) from musicians presented with a musical score and instructed to form an auditory image of the music in the score. An initial activation of occipital cortex spread to midline parietal and then to left temporal auditory association areas and right premotor areas. Schürmann et al. suggested this pattern would be expected if visual representation of the score was converted into auditory imagery. However, although Waters et al., Kalakosi, and Schürmann et al. suggested auditory imagery played a causal role in their findings, none of these papers reported independent evidence that auditory imagery was actually generated.[1]

Brodsky et al. (2003; 2008) presented musicians with an elaborated musical score within which a well-known melody had been embedded. The embedded melody was not obvious to visual inspection, but Brodsky et al. hypothesized the embedded melody should be more obvious to the "mind's ear." Participants' reading of the score was accompanied by rhythmic (tapping), phonatory (humming), or auditory (listening to a recording of someone else humming) interference, or no

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[1] As discussed by Zatorre and Halpern (2005) and by Hubbard (2010), some researchers appear to assume that instructing participants to generate and use an image offers a sufficient basis for concluding that any resultant pattern of brain activation or behavioral outcome reflects the generation and use of imagery. However, it is possible that many experimental tasks might be accomplished with or without imagery or that other forms of representation or strategies might produce an outcome consistent with what might be produced by imagery. In both brain imaging studies and behavioral studies, claims regarding imagery should be accompanied by behavioral data that images were actually generated and used in the experimental task. For the sake of completeness, studies that suggest a role for imagery are included in this chapter, but it is noted when those studies do not provide sufficient evidence that auditory imagery was actually generated and used in the experimental task.

interference. Participants then listened to a melody and judged whether that melody had been embedded within the score. Recognition of the embedded melody was disrupted more by phonatory interference during reading than by rhythmic or auditory interference. Brodsky et al. (2008) also found that muscle activity near the vocal folds was higher during reading of a musical score than during a control activity. Brodsky et al. (2003, 2008) concluded phonatory processing contributed to notational audiation. It could be hypothesized that notational audiation would facilitate sight-reading of music (e.g., by priming appropriate finger movements for performance), but Kopiez et al. (2006) found better sight-readers did not perform better on Brodsky et al.'s embedded melody task.

4.3.4   Speech and Text

Stuart and Jones (1996) presented participants with a visual word and asked them to form an image of (a) what that word would sound like when pronounced or (b) the sound typically made by the object the word referred to. Auditory imagery of how words sounded primed recognition of those words, and auditory imagery of how objects sounded primed recognition of those environmental sounds. Geiselman and Glenny (1977) presented participants with recordings of a male voice and of a female voice. Participants were then visually presented with pairs of words and asked to image the words being pronounced in the male voice, female voice, or their own voice. Participants were more likely to subsequently recognize words pronounced in the same voice as they had imaged during learning. Johnson et al. (1988) presented lists of words that were spoken or to be imaged in a particular voice, and participants later exhibited difficulties in discriminating between words that were spoken and words that were imaged. Priming effects of imaged words, sounds, and voices in Stuart and Jones and in Geiselman and Glenny, and difficulty in discrimination in Johnson et al., are consistent with similarities in representation of auditory perception and imagery and with priming effects in Farah and Smith (1983), Hubbard and Stoeckig (1988), and Crowder (1989).

Tian and Poeppel (2010) acquired MEG from participants who articulated, imaged articulating, listened to, or imaged listening to the syllable "dah" (cf. Meyer et al. 2007). Articulation imagery did not activate primary motor cortex but did activate posterior parietal cortex. Activation patterns for listening and for imaged listening were similar. The neural response after imaged articulation was similar to the neural response for listening, and Tian and Poeppel argued that auditory cortex was activated after imaged articulation (by auditory efferent information). Tian and Poeppel suggested similarity of topographies of listening and of imaged listening supported the hypothesis that perceptual neural systems are engaged during generation of imagery. Jäncke and Shah (2004) acquired fMRI of participants trained to image hearing a specific syllable when they saw a flashlight. Their participants exhibited hemodynamic increases in auditory cortex in the region of the superior temporal gyrus near the planum temporale during trials in

which they reported image formation; however, there was no activation in Heschl's gyrus or other areas of primary auditory cortex, and this is consistent with previous studies (e.g., Bunzeck et al. 2005; Daselaar et al. 2010; Zatorre et al. 1996; Zatorre and Halpern 2005).

Aleman and van't Wout (2004) had participants form speech images of bisyllabic words and indicate which syllable carried the stress. Performance was decreased by concurrent articulation of an irrelevant sound and by finger tapping, but articulation had less effect on a visual imagery control task. Aleman et al. (2005) acquired fMRI from participants in a similar task. Perception and imagery each resulted in activation of supplementary motor area, inferior frontal gyrus, superior temporal gyrus, and superior temporal sulcus; however, superior temporal sulcus was not activated if participants viewed a written word and made a semantic judgment about the word. Aleman et al. suggested that processing of metric stress in perception and in imagery relies in part on superior temporal sulcus and superior temporal gyrus. Aziz-Zadeh et al. (2005) had participants count the number of syllables in a letter string. Response time was faster if participants generated speech imagery than if they generated actual speech, and response time increased with the number of syllables. Additionally, application of rTMS over Broca's area and motor areas in the left hemisphere increased response times. Curiously, application of rTMS over motor areas interfered with actual speech but not with imaged speech (cf. Aleman et al. 2005).

Reisberg et al. (1989; Smith et al. 1995) examined whether an analogue of the verbal transformation effect (in which a stream of rapid repetitions of a word is eventually parsed as a stream of rapid repetitions of a different word, e.g., a stream of rapid repetitions of the word "life" is eventually heard as a stream of rapid repetitions of the word "fly," Warren 1968) occurred in auditory imagery. Reisberg et al. had participants image repetitions of the word "dress," and participants subsequently could report the alternate parsing of "stress" only if they were able to subvocalize during imagery (for discussion, see Chap. 12). Rudner et al. (2005) had participants mentally reverse an aurally presented letter string and then compare that reversed string to a second aurally presented letter string. A control condition involving judgment of whether two words rhymed was also examined. Dynamic manipulation of auditory imagery in the reversal task activated bilateral parietal lobes and right inferior frontal cortex, and Rudner et al. suggested these structures provided a link between language processing and manipulation of imagery. Interestingly, these structures are similar to those used in manipulation of visuospatial information in mental rotation (Zacks 2008) and in temporal reversal of a melody (Zatorre et al. 2010).

Abramson and Goldinger (1997) found participants reading silently required more time to respond to visual presentations of words containing long vowel sounds than to visual presentation of words containing short vowel sounds. Alexander and Nygaard (2008) found participants read passages more slowly if those passages had been attributed to a speaker with a slow speaking rate (cf. Kosslyn and Matt 1977). Brunyé et al. (2010) had participants read descriptions rich in auditory imagery (e.g., the orchestra tuned their instruments as the patrons found their seats).

Participants then heard sounds they judged as real (i.e., recorded from actual events) or fake (i.e., computer-generated). Participants were faster to correctly classify a sound as real if that sound matched an auditory image that would have been evoked by the description. Kurby et al. (2009) had participants listen to dialogs between characters. Participants then read scripts, and during reading, they were interrupted with an auditory retention task in the voice of a character previously listened to or in a different voice. Participants were faster with matching than with mismatching voices on familiar scripts. Although Brunyé et al. and Kurby et al. postulated a causal role for auditory imagery, neither paper reported independent evidence that auditory imagery was actually generated.

4.3.5   Environmental Objects

As noted earlier, Intons-Peterson (1980) and Intons-Peterson et al. (1992) examined auditory imagery of loudness and pitch, respectively, of common environmental objects. Stuart and Jones (1996) reported an image of a sound of a common environmental object primed recognition of other sounds from the same category (e.g., sounds of transport, nature, household objects). Schneider et al. (2008) presented participants with visual pictures of objects and with auditory recordings of sounds. Participants judged whether the sound was appropriate to the pictured object, and they were faster if the sound was appropriate. Bunzeck et al. (2005) acquired fMRI from participants presented with (a) visual pictures and instructed to generate an auditory image of the appropriate sound or (b) visual pictures accompanied by appropriate or inappropriate sounds. If participants generated imagery of an appropriate sound, there was activation in secondary but not primary auditory cortex, whereas if an appropriate sound was presented, there was bilateral activation in primary and secondary auditory cortex. Wu et al. (2006) had participants (a) view a picture of an animal or (b) view a picture of an animal and generate an auditory image of the sound made by that animal. P2 and the LPC were larger in the imagery condition, and Wu et al. suggested this reflected generation of auditory imagery.

4.4   Individual Differences

The possibility of individual differences in imagery has been of interest to many investigators, and potential individual differences are considered in many chapters in this volume. Individual differences considered here involve the vividness of auditory imagery, relationship of auditory imagery to auditory hallucination, developmental changes in auditory imagery, and whether auditory imagery is related to musical training.

4.4.1 Vividness

As noted in Hubbard (2010), there has been relatively little research on differences in vividness of auditory imagery in nonclinical populations. Baddeley and Andrade (2000) suggested vividness of auditory imagery was related to the strength of (or lack of interference with) representation of auditory information within the phonological loop of working memory (see Chap. 12); more specifically, increased vividness requires that more sensory information be available to appropriate systems in working memory. Tracy et al. (1988) suggested visual imagery is more vivid than is auditory imagery, but Kosslyn et al. (1990b) and Tinti et al. (1997) found that auditory images were rated as more vivid than were visual images. Additionally, Tinti et al. found that interacting auditory images were rated as more vivid than were noninteracting auditory images. Reports of increased vividness of auditory imagery are linked with increased activation of secondary auditory cortex (Olivetti Belardelli et al. 2009; Zatorre et al. 2010) and of right globus pallidus and left inferior ventral premotor cortex (Leaver et al. 2009).

There is not yet a single widely accepted scale for assessing vividness of auditory imagery, but several different scales have been used as follows (see also Chap. 14).

4.4.1.1 Questionnaire on Mental Imagery

Betts (1909) developed the Questionnaire on Mental Imagery (QMI) to measure an individual's ability to form images in different sensory modalities. Items addressing auditory imagery involve ratings of the clarity and vividness of images of a teacher's voice, familiar melodies that were played or sung, and various environmental sounds. Participants rate vividness on a 1 (perfectly clear and vivid as the original experience) to 7 (no image present at all) scale. However, the QMI confounds clarity and vividness and the anchor terms are ambiguous (McKelvie 1995; Richardson 1977; Willander and Baraldi 2010). A shortened form of the QMI (based on principle components analysis) involving five items for each modality of imagery was proposed by Sheehan (1967), but the revised QMI appears to suffer from the same shortcomings of confounded clarity and vividness and of ambiguity. Also, test–retest reliability of the QMI and the revised QMI are low.

4.4.1.2 Auditory Imagery Scale

Gissurarson (1992) developed the Auditory Imagery Scale (AIS), which was based on participant ratings of auditory images of seven different items on a 1 (very clear sound/noise) to 4 (no sound/noise) scale. Sounds to be imaged included footsteps coming upstairs, water dripping, and a favorite piece of music. The items all loaded onto a single factor and, coupled with the correlation of ratings from the AIS with

ratings from the Vividness of Visual Imagery Questionnaire (VVIQ; Marks 1995), led Gissurarson to suggest a general imagery capacity for (at least) visual and auditory modalities. Curiously, VVIQ ratings, but not AIS ratings, correlate with social desirability (Allbutt et al. 2008).

4.4.1.3   Auditory Imagery Questionnaire

Hishitani (2009) suggested that there might not be enough items on the AIS to allow extraction of multiple factors, and so he developed the Auditory Imagery Questionnaire (AIQ). The AIQ involved an initial generation of descriptions of 42 items, and from these, 12 items were then selected, all of which were reported to be familiar and frequent. Each imaged sound was rated on a 1–5 scale with low ratings indicating high clarity and vividness. A partial hierarchical model of responses revealed components that mapped onto the inner voice and inner ear distinction in auditory imagery (cf. Smith et al. 1995, and Chap. 12). Ratings from the AIQ correlate with ratings from the VVIQ, and this is consistent with the correlation between the AIS and the VVIQ reported by Gissurarson (1992). Also, participants with greater musical experience reported greater vividness with the AIQ, and participants with high vividness scores exhibited better pitch memory.

4.4.1.4   Clarity of Auditory Imagery Scale

Willander and Baraldi (2010) suggested the AIS is problematic in that the method of establishing dimensionality of the solution was not adequately reported and the labeling of the verbal anchors was not clear. They developed a 16-item scale in which imaged sounds (e.g., a clock ticking, dog barking, paper being torn) are rated on a 1 (not at all clear) to 5 (very clear) scale, which they referred to as the Clarity of Auditory Imagery Scale (CAIS). Factor analysis revealed four factors with eigenvalues greater than one, but given the results of a minimum average partial test, only one factor was extracted. There were no effects of age or gender. The original scale was developed in Swedish and translated into English. A Spanish version of the CAIS has been developed (Campos and Perez-Fabello 2011), and in the Spanish version, three factors were identified, and scores correlated positively with ratings from the VVIQ-2 and negatively with the auditory scale of the QMI (low scores on the QMI indicate greater clarity and vividness).

4.4.1.5   Bucknell Auditory Imagery Scale

The Bucknell Auditory Imagery Scale (BAIS) has separate scales for vividness of auditory imagery and for control of auditory imagery. The vividness scale consists

of 14 imaged sounds (e.g., voices, musical instruments, rain) that are rated on a 1 (no image present at all) to 7 (as vivid as actual sound) scale. The control scale consists of 14 pairs of imaged sounds (the first involving a stimulus within a specific setting, and the second involving a change within the same setting, e.g., a dentist drill and then the soothing voice of the receptionist, a song on the car radio and then the screech of tires as the car comes to a halt) that are rated on a 1 (no image present at all) to 7 (extremely easy to change the image) scale. Zatorre et al. (2010) found that vividness and control were positively correlated and that BAIS ratings correlated with activation of the right parietal lobe and planum temporale. Factor analysis, reliability, or validity information on the BAIS has not yet been published.

4.4.2 Auditory Hallucination

Auditory verbal hallucinations have been suggested to reflect abnormal auditory imagery (e.g., Bentall and Slade 1985; Jones and Fernyhough 2007; Seal et al. 2004; Smith 1992); for example, individuals with auditory verbal hallucinations might be unable to distinguish speech that occurs in auditory imagery from actual speech in the external world (e.g., Bick and Kinsbourne 1987; Frith and Done 1988). Evidence consistent (e.g., Mintz and Alpert 1972; Slade 1976) and inconsistent (e.g., Brett and Starker 1977; Starker and Jolin 1982) with this suggestion has been reported. Aleman et al. (1999) found participants with greater predisposition to hallucination reported more vivid visual and auditory imagery but scored lower on a measure of imagery vividness involving imaginal comparisons of different stimuli. Barrett and Etheridge (1992) found nearly half of a pool of 585 undergraduates reported having a verbal auditory hallucination at least once a month, and the presence of hallucinations was not correlated with psychopathology or with measures of social conformity. Barrett (1993) reported (nonclinical) participants more predisposed to hallucinations reported more vivid imagery than did participants less predisposed to hallucinations, but the predisposition to hallucination did not influence reported control of imagery.

McGuire et al. (1995) acquired PET imagery of patients with schizophrenia and control participants. If participants imaged sentences spoken in their own voice, there were no differences between groups, but if participants imaged sentences spoken in another person's voice, patients exhibited reduced activity in left middle temporal gyrus and rostral supplementary motor area. Linden et al. (2011) acquired fMRI of nonclinical auditory hallucinations and of auditory imagery, and they reported increased activity in superior temporal sulcus, frontal and temporal language areas in the left hemisphere and right hemisphere homologues, and supplementary motor area in hallucinations and in imagery. Activity in supplementary motor area preceded activity in auditory areas during voluntary imagery, but activity in supplementary motor area and auditory areas was instantaneous during hallucinations; Linden et al. suggested this difference in timing

reflected the difference between voluntary auditory imagery and involuntary auditory hallucinations (cf. Shergill et al. 2004). However, Evans et al. (2000) noted that auditory imagery of speech and auditory hallucination are unlikely to be related in a direct or simple way.

4.4.3   Development

One of the earlier and well-known investigations of mental imagery in children, that of Piaget and Inhelder (1971), contains little mention of auditory imagery, and subsequent studies of development of imagery usually focused on visual imagery (e.g., Kosslyn et al. 1990a; Pressley and Levin 1977). Relatively little is known about development of auditory imagery, and as Mannering and Taylor (2008–2009) noted, studies of auditory imagery in children typically focused on musical imagery and the role of musical training in fostering cognitive development (e.g., Ho et al. 2003; Rauscher et al. 1997) or the relationship of auditory imagery to deafness or blindness (e.g., Mythili and Padmapriya 1987). Tahiroglu et al. (2011–2012) interviewed 5-year-old children about visual and auditory imagery in the children's interactions with imaginary companions, and the children completed tasks that assessed their visual imagery, auditory imagery for conversations, verbal ability, and working memory. Children who reported it was easy to interact with imaginary companions were more likely to show responses that suggested use of imagery on the tasks than were children who reported difficulties in interacting with imagery companions or who did not have an imaginary companion.

Mannering and Taylor (2008–2009) presented 5-year-old children and adults with tasks involving static or dynamic visual or auditory images. In a static auditory imagery task, children and adults compared the sounds of two animals (e.g., which is louder, a barking dog or a roaring lion?), and in a dynamic auditory imagery task, they adjusted the loudness of an image of one animal to match the loudness of an image of another animal (e.g., cat meowing to match a lion roaring). In the static task, response times for adults decreased with increases in the difference in initial loudness, but response times for children were not related to differences in initial loudness. In the dynamic task, response times for children and for adults were positively correlated with the magnitude of the difference in initial loudness levels of the two stimuli. Cohan (1984) had participants 6 to 21 years of age use auditory imagery in completion of a melody. Participants in the 9–21 age group performed best, and performance declined with younger ages. Also, Cohan reported each age group performed better on a static imagery task than on a dynamic imagery task. In Mannering and Taylor and in Cohan, children's auditory images did not exhibit the flexibility of adults' auditory images, and this is consistent with findings on development of visual imagery.

4.4.4 Musical Ability and Training

A common suggestion in the literatures on auditory imagery and on music cognition is that better performance on music-related tasks is linked with better auditory imagery (e.g., Seashore 1938/1967); however, it has been difficult to determine if musical ability and training is causal in development of auditory imagery or vice versa. Gissurarson (1992) noted that participants with greater musical experience tended to report more vivid imagery on the AIS. Kornicke (1995) suggested auditory imagery aids sight-reading, and this is consistent with findings by Waters et al. (1998) that better sight-readers exhibit larger harmonic priming. However, Kopiez et al. (2006) found better sight-readers do not perform better on an embedded melody task, and this suggests better sight-readers do not exhibit better auditory imagery. Seashore 1938/1967 discussed anecdotal reports that famous composers including Beethoven, Berlioz, Mozart, Schumann, and Wagner relied on auditory imagery during musical composition, but there are few data on this issue (see Mountain 2001). Also, the direction of causation in links between musical training and intelligence more generally are not well established (see Schellenberg 2011).

Aleman et al. (2000) asked participants which of two lyrics from a well-known melody would be sung on a higher pitch (cf. Halpern 1988a; Zatorre and Halpern 1993; Zatorre et al. 1996). Participants with musical training made fewer mistakes than those without, although there were no differences in response times. Keller and Koch (2006; 2008; Keller et al. 2010) had participants respond to different sequences of visually presented colors by pressing different keys, and each key was associated with a specific pitch. Participants with musical training were influenced by different pairings of pitches and key positions, but participants without musical training were not (cf. Elkin and Leuthold 2011). Kalakoski (2007) suggested better memory for note positions on a musical staff for musicians than for nonmusicians was due to notational audiation. Hubbard and Stoeckig (1988) found participants with musical training exhibited trends for stronger priming from an imaged prime. Halpern (1992) found participants with musical training exhibited greater flexibility in the range of tempi at which they reported they could image a familiar melody. Cahn (2008), Highben and Palmer (2004), and Theiler and Lippman (1995) suggested auditory imagery can aid musical practice.

Janata and Paroo (2006) reported participants with musical training exhibited better pitch acuity and better temporal acuity in auditory imagery. Similarly, Cebrian and Janata (2010b) found acuity for images of pitch and the ability to form accurate pitch images across a greater variety of tasks was increased for participants with more musical training. Magne et al. (2006) found children who had received musical training could detect pitch violations at the ends of phrases in music or in language better than could children who had not received musical training. Magne et al. suggested some aspects of pitch processing develop earlier for music than for language and that their findings reflect positive transfer between

melodic processing and prosodic processing. Herholz et al. (2008) acquired MEG from musicians and nonmusicians presented with familiar melodies. Participants listened to the beginning of a melody and then continued the melody in auditory imagery. They then heard a note that was a correct or incorrect further continuation of the melody. Musicians but not nonmusicians exhibited mismatch negativity to an incorrect note, and Herholz et al. suggested musical training improved auditory imagery. Consistent with this, Hishitani (2009) reported participants with more musical experience reported increased vividness of auditory imagery.

4.5 Auditory Properties of Auditory Imagery

Properties regarding preservation of structural information and temporal information in the image of an auditory stimulus, whether information in auditory imagery influences expectancies regarding subsequent stimuli, and whether auditory imagery involves the same mechanisms and cortical structures involved in auditory perception, are considered. Multisensory and crossmodal properties (e.g., kinesthetic, mnemonic) of auditory imagery are discussed in Chap. 12.

4.5.1 Structural Properties

A range of findings supports the claim that auditory imagery preserves structural properties of imaged stimuli. Such structural properties include pitch distance (Intons-Peterson et al. 1992), loudness distance (Intons-Peterson 1980), absolute pitch of the starting tone of a melody (Halpern 1989, 1992), timbre (Halpern et al. 2004), musical contour (Weber and Brown 1986), melody (Zatorre et al. 2010), intervening beats in a musical stimulus (Halpern 1988a; Halpern and Zatorre 1999), tempo of music (Halpern 1988b) and of speech (Abramson and Goldinger 1997), and harmonic context (Vuvan and Schmuckler 2011). These structural similarities allow auditory imagery to prime a subsequent percept on the basis of pitch (Farah and Smith 1983), harmonic relationship (Hubbard and Stoeckig 1988), timbre (Crowder 1989; Pitt and Crowder 1992), and category (Stuart and Jones 1996). However, a few findings are not consistent with the claim that auditory imagery preserves structural properties of imaged stimuli, and these include the relative difficulty in detecting an embedded melody (Brodsky et al. 2003, 2008) or detecting an alternative interpretation of an auditory image (e.g., Reisberg et al. 1989; Smith et al. 1995). Also, imaged loudness does not appear to be a necessary part of an auditory image (Intons-Peterson 1980, but see Hubbard 2010; Wu et al. 2011). Overall, auditory imagery appears to preserve most of the structural properties of auditory features and objects.

4.5.2 Temporal Properties

A range of findings supports the claim that auditory imagery preserves temporal properties of imaged stimuli. Such temporal properties include more time being required to transform an imaged pitch a greater pitch distance (Intons-Peterson et al. 1992), transform an imaged loudness a greater loudness distance (Intons-Peterson 1980), scan across more beats in an imaged melody (Halpern 1988a; Zatorre and Halpern 1993; Zatorre et al. 1996), count more syllables in an imaged letter string (Aziz-Zadeh et al. 2005), respond to words containing long vowel sounds than to words containing short vowel sounds (Abramson and Goldinger 1997), and generate a more complex auditory stimulus (Hubbard and Stoeckig 1988). An auditory image of a melody appears to specify a tempo similar to the tempo at which that melody is usually perceived or performed (Halpern 1988b), and the temporal accent pattern of meter is preserved in auditory imagery (Vlek et al. 2011). However, temporal acuity is weaker than pitch acuity in auditory imagery (Janata and Paroo 2006). The time required to generate an auditory image does not appear related to subjective loudness of that image (Intons-Peterson 1980), but as noted in Hubbard (2010), such a finding argues against the hypothesis that auditory imagery preserves temporal information only if it is presumed the subjective loudness of an image must be generated incrementally. Overall, auditory imagery appears to preserve most of the temporal properties of auditory features and objects.

4.5.3 Auditory Expectancy

Neisser (1976) proposed a "perceptual cycle" in which imagery was a type of "detached schema" that reflected expectancies regarding what was likely to be encountered in the environment. A range of findings supports the claim that auditory imagery involves expectancies. Such findings include spontaneous occurrence of auditory imagery during a silent interval in a familiar song (Kraemer et al. 2005) or during a silent interval between songs in a familiar CD (Leaver et al. 2009), emitted potentials in the absence of an expected note (Janata 2001), priming of harmonically related chords (Hubbard and Stoeckig 1988), and spontaneous generation of a visual image of a stimulus if participants generate an auditory image of the sound of that stimulus (Intons-Peterson 1980). Such findings appear stimulus specific, but auditory imagery can also be generally facilitating (Sullivan et al. 1996). However, findings that loudness information is not necessarily incorporated into an auditory image (Intons-Peterson 1980; Pitt and Crowder 1992; but see Wu et al. 2011), phonological components of speech are not necessarily activated during silent reading (Kosslyn and Matt 1977; but see Alexander and Nygaard 2008), and auditory imagery of the sound made by an animal does not automatically occur upon visual presentation of a picture of the animal (Wu et al. 2006) suggest that not all expectancies necessarily influence auditory imagery.

4.5.4   Relation to Auditory Perception

A range of behavioral findings supports the claim that auditory imagery involves the same mechanisms involved in auditory perception. Such findings include detection of a faint auditory stimulus is decreased if an observer is generating auditory imagery (Segal and Fusella 1970), generation of an auditory image is decreased if an observer is attempting to detect an auditory stimulus (Tinti et al. 1997), imaged pitch and perceived pitch involve a vertical dimension (Elkin and Leuthold 2011), imaged pitch and perceived pitch are interpreted within a relevant tonal context (Hubbard and Stoeckig 1988; Vuvan and Schmuckler 2011), classification of a perceived sound is faster if that sound matches a previous auditory image (Brunyé et al. 2010), and participants are faster in processing verbal script information if the voice for a character matches the voice from previous experience with that character (Kurby et al. 2009). Also, and as noted earlier, judgments of whether an imaged pitch matched a subsequently perceived pitch are facilitated if the pitch and timbre of the imaged pitch match the pitch (Farah and Smith 1983; Hubbard and Stoeckig 1988) or timbre (Crowder 1989; Pitt and Crowder 1992) of the perceived pitch, but do not seem to be influenced by whether loudness in the image matches loudness in the percept (Pitt and Crowder 1992). In general, auditory imagery facilitates perception of a subsequent auditory stimulus if content of the image matches the expected stimulus (although exceptions have been found, e.g., Okada and Matsuoka 1992).

4.5.5   Cortical Structures

Many findings that suggest auditory imagery preserves structural and/or temporal properties of auditory stimuli, and that auditory imagery and perception use similar mechanisms, also suggest auditory imagery involves many of the same cortical structures as auditory perception. Also, patients with a right hemisphere lesion perform more poorly on pitch discrimination in imagery and in perception (Zatorre and Halpern 1993), application of rTMS to the right hemisphere disrupts pitch discrimination (Halpern 2003) and speech and imaged speech (Aziz-Zadeh et al. 2005), lower-pitched or louder images and percepts evoke larger N1 and LPC (Wu et al. 2011), decomposition of EEG for perceived and imaged music correlates highly (Schaefer et al. 2009, 2011), MEG for perception and imagery are similar (Tian and Poeppel 2010), N1 in perception and LPC in imagery are similar (Wu et al. 2011), and imaged reversal of linguistic (Rudner et al. 2005) or musical (Zatorre et al. 2010) stimuli activates cortical structures relevant in manipulation of sensory information. Superior temporal gyrus, frontal and parietal lobes, and supplementary motor cortex are active in perceived or imaged pitch (Zatorre et al. 1996) and timbre (Halpern et al. 2004) discrimination. Planum temporale is activated by auditory imagery of environmental sounds (Bunzeck et al. 2005) and might be related to vividness

(Zatorre et al. 2010). Primary auditory cortex does not appear activated in auditory imagery (e.g., Bunzeck et al. 2005; Daselaar et al. 2010; Halpern et al. 2004).

4.6   Conclusions

Auditory imagery preserves information regarding many auditory features (e.g., pitch, loudness, timbre, duration, tempo, rhythm, duration) and preserves information regarding many auditory objects (e.g., musical contour and melody, musical key and harmony, speech and text, common environmental stimuli). There are potential individual differences in the vividness of auditory imagery, relationship of auditory imagery to auditory hallucination, development of auditory imagery, and relationship of auditory imagery to musical ability and training, but clarification of these issues awaits future research. Studies of imagery of auditory features and imagery of auditory objects suggest several broad properties of auditory imagery, including preservation of structural (e.g., pitch distance, harmonic context, phonology) and temporal (e.g., tempo, rhythm, duration) information, influences of expectations regarding current and subsequent stimuli (e.g., spontaneous imagery, priming of subsequent responses), similarity to mechanisms of auditory perception (e.g., effects of pitch height, priming of subsequent responses), and instantiation in many (e.g., temporal gyri, planum temporale), but not all (e.g., primary auditory cortex), of the cortical structures used in auditory perception. Auditory imagery captures important information regarding auditory stimuli and allows individuals to represent that information in a form that appears to recreate aspects of auditory experience, and this presumably optimizes potential responding to those stimuli.

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Chapter 5
Olfactory and Gustatory Mental Imagery: Modulation by Sensory Experience and Comparison to Auditory Mental Imagery

M. Bensafi, B. Tillmann, J. Poncelet, L. Przybylski, and C. Rouby

Abstract Olfactory and gustatory mental images are defined as short-term memory representations of olfactory or gustatory events that give rise to the experience of "smelling with the mind's nose" or "tasting with the mind's tongue." This chapter reviews converging evidence supporting the view that, as with visual mental images, odor and taste mental images preserve some aspects of olfactory and gustatory percepts. The variability that affects both types of imagery is also considered in an experiment comparing the effect of experience on chemosensory mental imagery and auditory mental imagery.

Keywords Mental imagery • Odor • Taste • Music • Variability • Experience

5.1 Introduction

Almost anyone can experience vivid visual scenes by imagining them. Cognitive psychologists define such visual mental images as short-term memory representations of visual events that give rise to the experience of "seeing with the mind's eye." Despite the dominance of the visual modality for humans, mental imaging seems accessible to "the mind's ear"; "the mind's nose"; to gustatory, tactile, and

M. Bensafi (✉)
CNRS, UMR5292, Lyon Neuroscience Research Center,
University Lyon, Lyon 69000, France

Université Claude Bernard, Lyon, 50 Avenue Tony Garnier, Lyon 69366, France
e-mail: bensafi@olfac.univ-lyon1.fr

B. Tillmann • J. Poncelet • L. Przybylski • C. Rouby
CNRS, UMR5292, Lyon Neuroscience Research Center,
University Lyon, Lyon 69000, France

kinesthetic modalities; and to motor representations as well. Creating internal representations of external events and conjuring them up is one of the most covert cognitive processes. Its vividness can, however, be measured subjectively, and scales have been developed for that purpose. For the chemical senses, recent research has provided both behavioral and physiological correlates of olfactory and, to a lesser extent, gustatory imagery. The first aim of this chapter is to review these findings, which converge in supporting the view that chemosensory, like visual, mental images conserve some aspects of sensory percepts. Here, we will also take into account a characteristic of mental imagery that is especially prominent in the chemical senses: variability between individuals. Because sensory systems are highly plastic and taste and olfactory cells are renewed along adult life, our second aim will be to present experimental data suggesting that part of this interindividual variation may be the result of sensory experience.

5.2   Olfactory and Gustatory Mental Images: Mechanisms and Variability

Evidence for an "inner nose" has been reported since 1990, suggesting that odor imagery and odor perception share some mechanisms. Lyman and McDaniel (1990) showed improvement in recognition memory of odors with imagery; Algom and Cain (1991) showed that the same power functions linked concentration and perceived intensity in both perceived and imagined mixtures; Carrasco and Ridout (1993) showed that multidimensional scaling of both perceived and imagined odor sets was based on the same main dimensions; and Djordjevic et al. (2004c) showed that imagining an odor lowered its detection threshold. Thus, certain overt measurements provide evidence for the existence of the covert mental process of odor imaging. A second step was made possible by neuroimaging tools. In parallel with the finding, in the visual modality, that primary visual cortex is activated during mental visual imaging (Kosslyn 2005), Djordjevic et al. (2005), using positron emission tomography, showed that imagination, like actual perception, of smells increases activation in primary (piriform cortex) and secondary (insula, orbitofrontal cortex) olfactory regions. Bensafi et al. (2007) used functional magnetic resonance imaging to measure brain activation in subjects who were alternating between smelling and imagining pleasant and unpleasant odors: Brain activity induced by imagining odors mimicked that induced by perceiving real odorants, not only with respect to the particular brain regions activated but also to its hedonic-specific pattern; for both real and imagined odors, unpleasant stimuli induced greater activity than pleasant stimuli in the left frontal portion of piriform cortex and left insula. Likewise, Plailly et al. (2012) showed that mental imaging of odors activated primary olfactory (piriform) cortex in perfumery experts.

In contrast to olfactory mental imagery, empirical evidence for an "inner tongue" is less clear. One reason for this may lie in the difficulty of imagining a taste alone because what we experience with foods is actually their flavor, which is a more

complex perception combining taste, odor, texture, and trigeminal input. Flavor challenges the taxonomy of our senses, being "object-oriented" rather than "sensation-oriented" (Auvray and Spence 2008). Moreover, flavor is not consciously decomposable into taste and smell (Prescott 1999). Thus, it is quite likely that mental imaging of tastes phenomenologically includes more than the taste modality and that what subjects imagine is objects (foods) rather than tastes. Two psychophysical studies by Djordjevic and colleagues (Djordjevic et al. 2004a, b) lend support to this view: Imagined odors influenced sweetness detection, and the imagined odors of a salty (soy sauce) or sweet food (strawberry) influenced the perception of saltiness and sweetness, respectively. However, the effect of taste imagery per se on taste detection or behavior remains unclear. One of the very few psychophysical studies on taste imagery did not measure taste perception, but rather salivation in response to imagined tastes: Drummond (1995) recorded salivation following both imagination of and stimulation with a sour candy, but found no effect of sourness imaging; contrary to expectations, mental imaging could not trigger such a brainstem reflex.

Functional imaging provides more convincing evidence for gustatory mental imagery than do the psychophysical findings. Two studies by Kobayashi compared taste perception and imagery using sweet, salty, bitter, and sour foods (Kobayashi et al. 2011; 2004). As expected, passive gustatory stimulation activated the insula/frontal operculum (primary taste areas) and the orbitofrontal cortex (secondary taste area). Gustatory imaging of the same foods likewise activated the insula and orbitofrontal cortex. In addition, taste imagery recruited non-gustatory regions: middle and superior frontal gyri. Likewise, Kikuchi observed neural activation in insula and orbitofrontal cortex during mental imaging of pickled plums, a famous sour food in Japan (Kikuchi et al. 2005). Taken together, these functional imaging findings are in accordance with the idea that the neural mechanisms underlying imagery generation are shared with the processing of the corresponding real sensations (Farah 1989; Kosslyn 2005).

Now, the question that ensues is as follows: By what mechanisms are odor images generated in the human brain? In the visual system, eye movements during visual imagery reenact those occurring during visual perception (Laeng and Teodorescu 2002; Spivey and Geng 2001). Like vision, olfaction integrates a sensory component (the smell itself for olfaction, visual input for vision) and a motor component (the sniff for olfaction, eye movement for vision). Research in both animals and humans suggests that sniffing, the motor component of olfaction, is a prominent feature of odor perception (Adrian 1942; Freeman 1981; Sobel et al. 1998).

A question raised in the recent literature is whether the olfactomotor system is involved in the generation of olfactory mental images. Such a mechanism was suggested for olfaction in a century-old study (Perky 1910).

Using psychophysical methods, Bensafi et al. (2003; 2005) found that olfactory imagery was accompanied by olfactomotor activity similar to that found during perception. Specifically, when asked to imagine smells, subjects spontaneously sniffed. Furthermore, they took a larger sniff when imaging a pleasant compared to an unpleasant smell, as if they were perceiving real smells, strengthening the notion that motor representations of odors are inseparable from their hedonic counterparts.

Moreover, sniffing did not merely accompany the mental representation of smell but contributed functionally to its quality: Blocking the sniff impaired the vividness of the olfactory image in the same way as blocking eye movements reduces the quality of visual imagery. Kleemann et al. (2009) reported convergent findings. They compared sniffing in three conditions: a control condition, where participants were not asked to perform any task; a perception task, in which they were asked to smell odors; and a mental imagery task in which they were asked to imagine odors. Both odor perception and odor imagery led to a significant increase in respiratory activity compared to the control condition. An important finding in Kleemann's report was that olfactomotor activity during odor perception and during odor imaging was similar in terms not only of respiratory volume but also of its temporal characteristics, as revealed by frequency spectrum analysis between conditions: The highest spectrum peak in all three conditions corresponded to the 0.25-Hz breathing frequency, but both odor imaging and odor perception were characterized by a large peak at 0.7 Hz, in contrast to the control condition. This finding strengthens the notion that olfactomotor activity during odor imaging mimics that during perception not only for one particular sniff parameter (respiratory volume) but also for the overall sniff pattern. Thus, motor representations are stored in long-term olfactory memory and contribute to the recall of smells. However, information in long-term memory is implicit and inaccessible (Kosslyn 2003), and the action of sniffing during imaging improves retrieval of long-term olfactory representations.

To the best of our knowledge, there are no similar studies that set out to examine a motor component of taste memory and images. As noted above, Drummond (1995) found no effect of taste imagery on salivation. Besides brainstem reflexes, recording tongue and swallowing movements could be an alternative way of exploring for a motor component of taste. Like odor images, mental representations of tastes seem to be linked with hedonics and motivation. For example, mental imaging of lemon or grapefruit juice can induce chills (shivers and goose bumps) and changes in electrodermal response (Grewe et al. 2011).

Evidence concerning visceral imagery for foods (but, to date, not for taste alone) comes from research on craving, a motivational state in which one feels compelled to seek and ingest a particular substance (see Chap. 20). Mental images of the substance or food are at the core of the craving experience (Kavanagh et al. 2005). Tiggemann and Kemps (2005) showed that mental imagery of recalled craving experiences is itself able to induce craving: Craving intensity correlated with the vividness of the food image, which, from subjective reports, appeared to be mainly visual, although also gustatory and olfactory.

Beside these emotional and motor mechanisms underlying the genesis of chemosensory mental images, an important characteristic of this type of imagery is its variability between individuals. Questionnaire studies have found large individual differences in the ability to form vivid olfactory images, suggesting the existence of "good" and "poor" olfactory imagers (Djordjevic et al. 2004a, b, c; Gilbert et al. 1998; Tomiczek and Stevenson 2009). In a psychophysical investigation, Bensafi and Rouby (2007) asked whether the wide variability between good and poor odor imagers derived from differences in their processing of real smells and of

emotion. Olfactory imaging ability was measured in 40 subjects on the Vividness of Olfactory Imagery Questionnaire (VOIQ) (Gilbert et al. 1998) and was correlated to performance on an olfactory test and the Physical Anhedonia Scale (Chapman et al. 1976), a test intended to access a wide variety of positive sensory experiences. Good olfactory imagers, defined primarily on the basis of the VOIQ, had lower anhedonia scores: They reported recalling more easily sensory pleasure, whereas poor olfactory imagers reported greater difficulty in recalling pleasant sensory experiences. Good and poor olfactory imagers also differed in their response to pleasant olfactory stimuli, the former rating pleasant smells as more familiar and more edible. On the other hand, no difference was found for odor detection or identification, suggesting it was in their experience of emotions and long-term representation of smells that good and poor olfactory imagers differed. Moreover, good and poor imagers differ in sniffing behavior: Good imagers sniffed all odors longer during olfactory stimulation (Rouby et al. 2009). Taken together, these results support the hypothesis of deeper or more emotional odor processing and better access to odor semantics in good olfactory imagers.

Neural differences between "good" and "poor" mental imagers during mental imagery tasks have been very little documented. Olivetti Belardinelli et al. (2009) recruited good/poor imagery subjects for seven sensory modalities (visual, auditory, kinesthetic, olfactory, gustatory, tactile, and somatic) and compared brain activation for these "high vivid" and "low vivid" participants in each modality. Subtraction of activations highlighted greater activity in sensory areas specific to visual, tactile, kinesthetic, somatic, and gustatory imagery (e.g., the left anterior insula was more activated for gustatory imagery) but no activation difference for olfactory or auditory imagery. It is important to note, however, that the number of participants (4 "high vivid" vs. 5 "low vivid") may be too small to be able to segregate these two populations in all imagery conditions. Future studies comparing a larger number of subjects differing significantly in mental imagery ability and assessing the vividness of their imagery during the scans may be helpful in this regard.

Thus, there are large individual differences in the self-reported ability to form vivid chemosensory mental imagery. Previous studies showed that this is not the result of experimental demand in that, as in real perception, good odor imagery is associated with differential olfactomotor strategies (Bensafi et al. 2005). In the same vein, "good" olfactory imagers, defined primarily on the basis of the VOIQ, rated pleasant smells as more familiar than "poor" olfactory imagers (Bensafi and Rouby 2007; Rouby et al. 2009), suggesting an effect of learning or experience on odor imagery ability. This possibility was explored by Stevenson et al. (2007), who tested whether difficulty in evoking odor images results from difficulty in naming odors. In their first experiment, they showed that hard-to-name odors were reported as being more difficult to evoke as olfactory (as compared to visual) images. A second experiment showed that participants who had learned the odor names during a training session were significantly better at imaging odors. This facilitation of imaging performance by names could also stem from better conscious access to odor images. That is, just as humans have unstable access to semantic information when experiencing an odor percept (Cain et al. 1998), they may have unstable access to olfactory

information when provided with the odor's verbal description. As underlined by Stevenson (2009), trying to form an olfactory image may generate a representation, but one to which the subject does not have conscious access: Learning names could thus bring together the conscious and unconscious representations of smells.

The above experiments thus suggest that language and experience may account for some of the interindividual variability in odor mental imagery ability. The long-term result of the effects of experience and language can be seen in professional practices such as perfumery, where experts, who are characterized by very high level of lexical knowledge of odors, often report good odor imagery ability (Gilbert et al. 1998; Plailly et al. 2012). Experts, however, are a very small portion of the population, and it is important to know whether the above effect can also be found in nonexperts. It should be borne in mind that the variability described in this chapter is mainly observed in novices. Perfumery is not a widespread everyday practice, but one important and very ordinary activity that involves smelling a wide variety of odor qualities is cooking. Preparing a main course, starter, or dessert uses a variety of ingredients (vegetables, meat, spices, fruits) with multisensory characteristics in which smell is of considerable importance for recognition and hedonic appreciation. Do lay people who are often exposed to odors—through cooking, for example—have better odor mental imaging ability? And does their expertise transfer to imagery in other modalities, or is it modality specific?

The effect of sensory experience on mental imagery ability and the question of intra-modality transfer were explored by Aleman et al. (2000) for the auditory modality. This study compared the performances of musicians and nonmusicians on three mental imagery tasks: (1) musical (comparing pitches of notes corresponding to the written lyrics of three familiar songs), (2) nonmusical auditory (comparing the acoustic characteristics of everyday sounds), and (3) visual (comparing the visual forms of objects). In each task, participants were presented with triads of stimuli written on cards and were required to select the odd one out: in the musical condition, lyrics of familiar songs; in the nonmusical auditory condition, common sounds (crying baby, laughing baby, meowing cat); and in the visual condition, the visual form of common objects (pumpkin, lettuce, tomato). As expected, the results showed that musicians outperformed nonmusicians in selecting the odd one out in both auditory tasks, suggesting that music training may improve both musical and nonmusical auditory imagery. A second result of interest was that there was no intergroup difference for the triad of visual forms, suggesting that sensory experience does not involve transfer of mental imagery ability across modalities.

The effect of sensory experience on imaging ability may be a general principle in brain functioning, so we tested whether people who are often exposed to odors, through cooking for instance, have better olfactory imagery than those who spend less time cooking. To enable comparison between modalities and to test whether olfactory experience involves a transfer of mental imagery ability in a different modality, we compared the effect of sensory experience on mental imagery in the olfactory and auditory domains: that is, with "olfactorily" and "auditorily" experienced participants (vs. controls) performing olfactory and auditory imagery tasks. A visual control condition was also added.

5.3 Effect of Sensory Experience on Mental Imagery: An Experimental Study on Odor Imagery and Musical Imagery

Based on the findings of Aleman et al. (2000), we assumed that sensory experience within a given modality should influence mental imagery ability in that modality but not another. This study therefore tested the dual hypothesis that musical mental imagery is improved in people who frequently practice music, while olfactory mental imagery is improved in those who frequently cook. To test this hypothesis, three groups differing in olfactory and/or in musical training ("cooking," "music," "control" groups) were asked to complete a two-step imaging task inspired by Aleman et al.'s paradigm: First, participants were asked to read two prime words (word A and word B) describing two fruits (or musical instruments) presented simultaneously on a computer screen. A third target word (word C) was then presented and the participant was asked to decide whether the odor of fruit C (or the timbre of the musical instrument C) was similar to that of A or of B. Within each group, response times and response accuracy were collected for each condition (odor imagery of fruits, OdorFruit; or timbre imagery of instruments, TimbInst) and were compared to a control task consisting in mentally imagining the size of the fruits (SizeFruit) or of the instruments (SizeInst). In addition, to ensure that the three groups did not differ in mental imagery abilities that did not involve their specific practices (olfactory or auditory), a control visual imagery task was performed, consisting in mentally imagining the size of various manufactured objects (SizeObj).

5.3.1 Method

5.3.1.1 Stimuli

We first selected three lists of words for fruits, musical instruments, and manufactured objects from the French-language Wikipedia website (see Appendix). Analysis of variance (ANOVA) revealed no significant difference between the lists for word frequency ($F[2, 69] = 0.143, p = 0.867$) or number of letters per word ($F[2, 69] = 0.485, p = 0.543$).

Secondly, since the tasks involved comparison of fruit odors, musical instrument timbres and the sizes of fruits, musical instruments, and manufactured objects, it was necessary to assess the similarities between stimuli in each list in terms of odor/timbre and size. This was achieved by a free-sorting procedure (Coxon 1982): 33 participants (mean age: 21.71 ± 1.46 years; 17 female) were asked to sort the 25 verbal stimuli of each list according to similarity in odor (for fruits), timbre (for musical instruments), and size (for all three lists). For each list, participants were presented 25 pieces of paper bearing the 25 words and were asked to form as many groups as they felt necessary. Thus, the number of groups should in principle range

between 1 (where all stimuli are lumped together in a single category) and 25 (where each stimulus forms its own category). No limit in sorting time or number of groups was imposed; the order of the five tasks was randomized for each participant.

Data were preprocessed before being scaled: Firstly, a matrix of co-occurrence between stimuli was drawn up for each participant, where grade 1 meant that two words were sorted into the same group and grade 0 otherwise. Secondly, these individual similarity matrices were then summed across participants, separately for each task (OdorFruit, TimbInst, SizeFruit, SizeInst, and SizeObj). The numbers per matrix cell ranged from 0 to 33 (where all 33 participants grouped the same two words together). The five co-occurrence matrices were then submitted to multidimensional scaling (MDS), a method classically used in similarity paradigms in olfactory and auditory research (Carrasco and Ridout 1993; Halpern et al. 2004; Schiffman 1974). Euclidian distances between each pair of stimuli in the three-dimensional spaces provided by the MDS were calculated as a measure of similarity between stimuli. An important point here was that the total variance explained by the three MDS dimensions was comparable between conditions (SizeObj: 92.9%, SizeInst: 91.3%, TimbInst: 88.7%, SizeFruit: 93.7%, OdorFruit: 93.4%). To select a triad, we first visually selected two words that were close on the 3-D graph, and then a third, distant, word. For this selected triad, the Euclidian distances between the three words were then measured according to their coordinates in the three dimensions (distance being short for similar and long for dissimilar words). This method of calculation was applied for each task, resulting in eight triads per task. As all triads contained two words that were similar, each triad was duplicated with one of the two similar words being used as "word C" (target). Finally, the resulting 16 triads were again duplicated, ending up with 32 triads per task with word A (or B) being presented on the left (or right) side of the screen. It is important to note that the distance between each pair of similar words did not significantly differ across tasks ($F[4, 35] = 2.246$, $p = 0.083$), suggesting that task difficulty was the same across conditions. Moreover, in order to avoid any effect of triad types across tasks referring to the same object (fruit or musical instrument), the same triads were used for both tasks involving fruits (OdorFruit and SizeFruit) or musical instruments (TimbInst and SizeInst).

5.3.1.2   Participants

We recruited 24 participants, divided into three groups ($n = 8$ per group; mean age $= 21.89 \pm 0.89$ years): a "cooking" group, a "music" group, and a "control" group. Participants were allocated to a particular group according to their responses on a preliminary questionnaire comprising the following two questions: (1) Do you cook? If yes, how often? (Several times a day? Once a day? Once a week? Less?) and (2) Do you play an instrument? If yes, did you have any musical training, and if so, for how long? Participants who cooked daily were allocated to the "cooking" group, and those who played an instrument and had had musical training were allocated to the "music" group. The "control" group comprised participants who
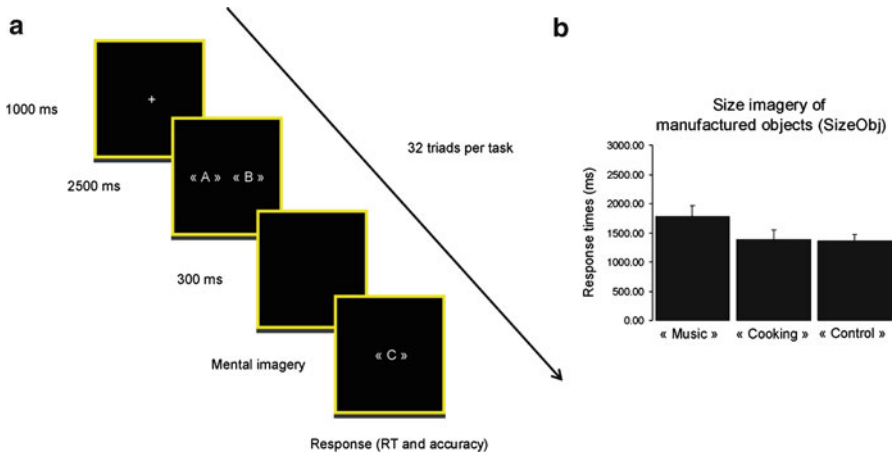
Fig. 5.1 (**a**) Typical sequence for an imagery trial. (**b**) Effect of sensory experience on response time during size imagery of manufactured objects. Error bars correspond to SEM

declared very rare culinary activities (less than once a week) and no musical practice.

5.3.1.3 Design and Procedure

Testing was performed in an experimental room designed for psychophysics experiments. To habituate the participants to the experimental setting, one practice trial was run for each task. The experiment comprised five blocks of 32 trials (one per task: OdorFruit, TimbInst, SizeFruit, SizeInst, and SizeObj). The order of trials and sessions was randomized between participants.

Each trial began with a 1,000-ms center-screen fixation, then the two prime words (A and B) initiating a particular triad were displayed for 2,500 ms. During that period, depending on the task, participants were asked to imagine either the size, the odor, or the timbre corresponding to words A and B (Fig. 5.1a). The third word (C: target) of the triad was then displayed (preceded by a 300-ms black screen), and participants were asked to imagine, as appropriate, its size, odor, or timbre and to make a speeded key-press response to indicate whether it was similar in that respect to word A or to word B.

5.3.2 Results

A first result of interest was that the control analysis comparing performance on the SizeObj task revealed no significant effect of group on response times ($F(2,21)=2.164$, $p=0.139$) (Fig. 5.1b). Secondly, response accuracy was comparable for the remaining
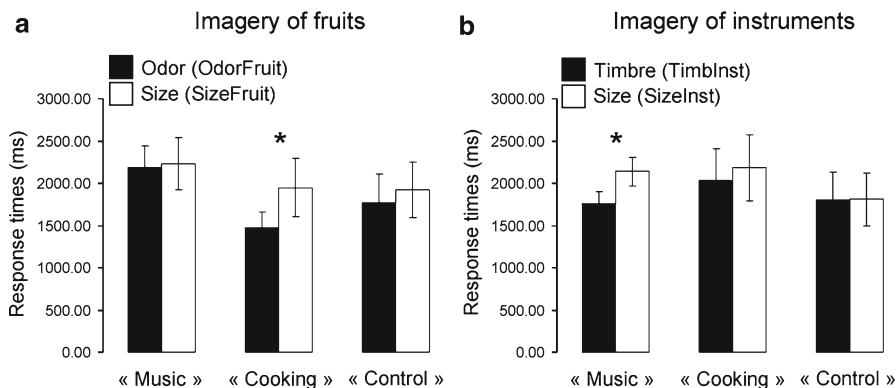
Fig. 5.2 (**a**) Effect of sensory experience on response time during odor and size imagery of fruits. (**b**) Effect of sensory experience on response time during timbre and size imagery of musical instruments. *$p<0.05$. Error bars correspond to SEM

conditions (SizeFruit: 69%, OdorFruit: 77%, SizeInst: 83%, TimbInst: 89%) and statistical analyses of response times were thus performed on correct responses. An ANOVA, with group ("cooking," "music," "control") as a between-factor and objects (fruits and musical instruments) and imagery type (sensory or size) as within-factors for response times, revealed no significant main effects of group ($F(2,21)=0.232$, $p=0.795$), objects ($F(2,21)=0.102$, $p=0.753$), and imagery type ($F(2,21)=3.692$, $p=0.068$), but a significant interaction between group, objects, and imagery type ($F(2,21)=3.532$, $p=0.047$). Mean comparisons (Student paired t-tests) revealed that (1) the "cooking" group responded faster during the OdorFruit task ($m\pm\text{SEM}=1468\pm194$ ms) than the SizeFruit task ($m\pm\text{SEM}=1946\pm345$ ms) ($p=0.033$), with no such difference between the TimbInst ($m\pm\text{SEM}=2036\pm375$ ms) and SizeInst tasks ($m\pm\text{SEM}=2185\pm389$ ms) ($p=0.306$); (2) the "music" group, on the other hand, responded faster during the TimbInst task ($m\pm\text{SEM}=1756\pm149$ ms) than during the SizeInst task ($m\pm\text{SEM}=2142\pm171$ ms) ($p=0.006$), with no such difference between the OdorFruit ($m\pm\text{SEM}=2192\pm249$ ms) and SizeFruit ($m\pm\text{SEM}=2235\pm306$ ms) tasks ($p=0.412$); and (3) response times in the "control" group did not differ between the OdorFruit ($m\pm\text{SEM}=1773\pm334$ ms) and SizeFruit ($m\pm\text{SEM}=1925\pm332$ ms) or TimbInstr ($m\pm\text{SEM}=1806\pm328$ ms) and SizeInstr ($m\pm\text{SEM}=1811\pm312$ ms) tasks ($p=0.157$ and $p=0.492$, respectively) (Fig. 5.2a, b).

To sum up, the main question addressed by this investigation was whether people who cook frequently or often play music have better odor or musical imaging mental ability, respectively, than those who are less involved in such activities. In addition, this experience can be expected to be modality specific and not to transfer to another modality (here, visual) (Aleman et al. 2000). The study assumed that performance in terms of response time corresponds to efficiency in imagining the respective sensory experiences. We found that response times reflected the expertise of participants experienced in music and cooking, respectively: Participants from the "cooking" group performed the OdorFruit task faster than the SizeFruit task,

while participants from the "music" group performed the TimbInst task faster than the SizeInst task. Taken together, these findings support the view that sensory practice has measurable effects on imaging ability, even in people without intensive professional training and although our two experienced groups ("music" and "cooking") may not have comparable expertise (our group who declared cooking every day may not have the same experience level as our group who declared playing an instrument over several years). They also suggest that sensory experience does not involve transfer of mental imagery ability across modalities, but rather domain-specific modulation of mental imagery ability, confirming Aleman et al.'s (2000) findings in the auditory domain. The specificity did not even extend to an irrelevant dimension of the same object (size), that is, the sensory experience concerned only the relevant dimension (i.e., odors of fruits or timbres of instruments).

5.4 Conclusions

This chapter reviewed converging evidence that, like visual mental images, odor mental images conserve some aspects of chemosensory percepts. In general, gustatory imagery is less well documented. An important question here is how these findings fit in with the current debate on the format (type of code) of the representations that underlie the experience of imagery. The issue is whether only propositional (Pylyshyn 2003) or also sensory (depictive) representations play a role in imaging (Kosslyn 2005). Arguments for the latter theory come from studies in the visual modality showing that primary visual cortex is activated during visual mental imagery. However, a difference between auditory and visual imagery has to be underlined. Only one study of auditory mental imagery (Kraemer et al. 2005) found activation in the primary auditory cortex (Zatorre 2007 for a review): Is vision the only modality in which imagery activates primary areas? The olfaction studies presented above suggest that this is not the case. We reviewed neuroimaging studies (Bensafi et al. 2007; Djordjevic et al. 2005; Plailly et al. 2012) suggesting that the format of odor images is not exclusively propositional but may include some sensory features and that generating imagery of olfactory events involves activation of primary olfactory structures common to real perception. Nevertheless, this evidence does not weigh definitively against the propositional theory or a fortiori against a role of semantics in generating odor images. As the famous perfumer Edmond Roudnitska noted: "If you have been in love with a woman who used Arpège and if, several years later, someone mentions in your presence the name Arpège, won't your mind call forth the particular form of this perfume just as quickly as if you had the bottle right under your nose?" (Roudnitska and Chastrette 1983, p 9). From a neural point of view, such a claim was borne out by a functional imaging study by Gonzalez et al. (2006), showing that verbal odor labels modulate activity patterns in human primary olfactory cortex, illustrating the power of names to evoke odor images.

Another important point raised by our chapter is the existence of large variability in olfactory mental imagery ability between individuals. We presented a

psychophysics study suggesting that sensory experience influences imagery ability in a domain-specific manner, even with only modest levels of practice. One mechanism underlying this effect of practice is neural plasticity, which is well documented in the auditory cortex (Pantev and Herholz 2011): Music listening can induce functional plasticity in nonmusicians, although to a lesser extent than active music training in professional musicians. Such neural plasticity has been suggested to occur in perfumers (Plailly et al. 2012) but has not been documented in cooks or nonprofessionals with varying levels of expertise. We know that olfactory perception is a dynamic process that heavily depends on past experience. The neural plasticity that allows this dynamic processing is expressed nearly ubiquitously in the olfactory pathway, from olfactory receptor neurons to the higher-order cortex, and includes mechanisms ranging from changes in membrane excitability to neurogenesis and apoptosis, via changes in synaptic efficacy (Mandairon and Linster 2009; Wilson and Sullivan 2011). This makes it likely that even moderate culinary practice could induce neural changes in olfactory brain areas. At the behavioral level, practice may have the effect of putting together the different components of mental imagery (emotional, sensorimotor, and verbal) and making them more easily available to working memory. Subsequently, there would be greater access to mental imagery from semantic memory. The result of such an effect of sensory experience is seen in experts in perfumery, who report good chemosensory imagery abilities (Gilbert et al. 1998; Plailly et al. 2012). One question that may be explored in future investigations is how such mental imagery abilities are used in creative thinking in these expert populations. Mental imagery has been identified as a core component of visual creativity (Finke 1996), and the influence of chemosensory mental imagery during creative ecological tasks (such as creating a new fragrance by a perfumer or a new dessert by a chef) remains unknown.

Appendix: Lists of Words

We first selected three lists of words for fruits, musical instruments, and manufactured objects from the French-language Wikipedia website:

- Fruits: http://fr.wikipedia.org/wiki/Liste_de_fruits
- Musical instruments: http://fr.wikipedia.org/wiki/Liste_des_instruments_de_musique
- Objects: http://fr.wikipedia.org/wiki/Liste_de_meubles_et_objets_d%27art

Redundancies or variations of the same word were first filtered out. Then, to control for frequency of use (as well as number of letters per word), word frequencies in a corpus of books were collected from the language resources website "Lexique 3" (http://www.lexique.org/); only words with a frequency approaching or exceeding one million hits were selected.

This twofold filtering selected three lists of 25 words each:

- Fruits: apricot, almond, pineapple, banana, blackcurrant, cherry, lemon, quince, date, fig, strawberry, raspberry, redcurrant, mandarin, mango, melon, cherry plum, blueberry, hazelnut, orange, grapefruit, peach, pear, prune, and grape
- Musical instruments: accordion, banjo, drum set, set of bells, clarinet, harpsichord, double bass, bagpipes, flute, guitar, harmonica, oboe, rattle, organ, piano, saxophone, whistle, drum, kettledrum, triangle, trumpet, tuba, violin, cello, and xylophone
- Manufactured objects: cradle, billiards, candle, bracelet, brooch, mug, filing cabinet, spoon, inkpot, fan, beaker, gourd, Chinese lantern, trunk, computer, folding screen, pitcher, pick, pouffe, ski, sofa, pen, screwdriver, case, and trowel

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Chapter 6
Motor and Kinesthetic Imagery

Helen A. Anema and H. Chris Dijkerman

Abstract This chapter aims to provide an overview of the functional, physiological, and neural characteristics of motor imagery. The literature reviewed shows that motor imagery shares many characteristics with motor executions, both at a behavioral and a physiological level. Furthermore, functional imaging studies show that imagining a movement activates a motor network that largely overlaps with that involved when actively performing a movement. However, the involvement of the primary motor cortex in motor imagery is still under debate. The range of behavioral, physiological, and neural effects of motor imagery also overlap with those reported during action observation, although activation of a motor network through imagery or observation may be less extensive than during action execution, with observation perhaps providing the least activation. Thus, the idea that motor imagery evokes similar motor representations as execution of movements may be used in a range of different applications such as motor (re)learning in sport psychology and rehabilitation of motor disorders. Moreover, brain-computer interfaces are now in development, using mental processes to interface with computers, which may be of great relevance to paralyzed patients.

Keywords Cognitive neuroscience • Motor system • Motor imagery • Kinesthetic imagery • Action observation • Imagery ability

H.A. Anema (✉)
Experimental Psychology, Helmholtz Institute, Utrecht University,
Heidelberglaan 2, Utrecht 3584 CS, The Netherlands
e-mail: h.a.anema@uu.nl

H.C. Dijkerman
Experimental Psychology, Helmholtz Institute, Utrecht University,
Utrecht, The Netherlands

Department of Neurology, University Medical Centre Utrecht,
Utrecht, The Netherlands
e-mail: c.dijkerman@uu.nl

6.1   Introduction

Motor imagery (MI) is the mental rehearsal of movements without the movements actually being executed. Imagine yourself, for example, throwing a ball, grasping a cup of tea, or running down the stairs. By accessing motor memories, motor imagery activates parts of the motor cortical network that largely overlap with those that are activated during real movement. In daily life, such images are used, for example, to prepare a movement, to anticipate the effects of this action, or simply just for intending to act. Motor imagery is widely used for the study of cognitive aspects of action control. It can be applied in various training and motor (re)learning settings both in the healthy and the clinical population. Moreover, it has recently been postulated as an essential function to build the "self," that is, to understand one's own actions and to learn how others' actions affect ourselves and how one's own actions determine the sense of being an agent (Jeannerod 2006).

In the early 1990s, Decety and Jeannerod (1996), among others, proposed that the mental states between action simulation and action execution share common underlying neural mechanisms. It takes, for example, a similar amount of time to mentally change the posture of your hand as it does when actually doing so, and the more familiar (less awkward) the posture is, the more similar the movement durations (Parsons 1994). Also, the speed-accuracy trade-off that has been found for movement execution (people usually move faster to larger than to smaller targets) applies to motor imagery (Decety and Jeannerod 1996). In one of Decety and Jeannerod's experiments, participants were instructed to imagine themselves walking through a gate. The various widths of these gates and the distances at which they were positioned affected the mental walking time. The longer the distance and the narrower the gate, the longer it took a participant to imagine walking through it (Decety and Jeannerod 1996). Since then, methods that allowed the scientists to "look" into the brain, such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), have been employed to further investigate the neural mechanisms underlying motor imagery.

In this chapter, we consider two major issues and themes within the field of motor imagery: the similarities and differences between real and imagined action at the behavioral, physiological, and neural levels and the similarities between imagined action and action observation. We also briefly consider prospects for various practical and clinical applications. These will be discussed more thoroughly in separate chapters in this book. However, before we proceed to what is known about motor imagery, we first present some conceptual information regarding motor imagery and the motor system itself.

6.2   The Motor System

Our movements are steered by a complex, hierarchical system of various neural structures in our brain, brain stem, and spinal cord that are tightly connected and work in concert to produce action (Gazzaniga et al. 2002; see Fig. 6.1). In short,
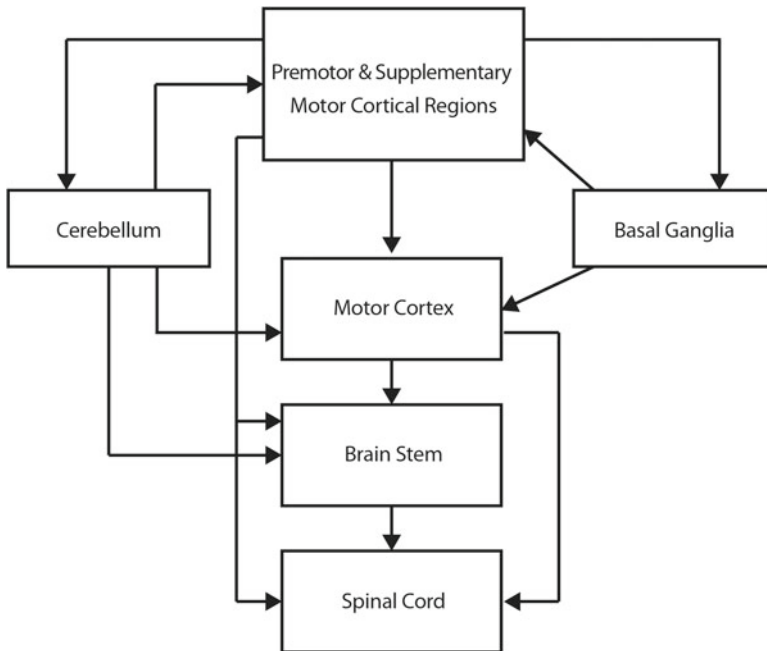
Fig. 6.1 A schematic depiction of the organization of the motor system. Muscles of the limbs and body are activated through neurons in the spinal cord. These receive input from nuclei in the brainstem and from various cortical areas. Cortical control may be indirectly, through connections with the brainstem motor nuclei, or directly, through corticospinal projections. Activation in the motor cortex is modulated by connections with the cerebellum and the basal ganglia (adapted from Gazzaniga et al. 2002)

muscles and tendons are activated via neural pathways (tracts) that originate in neurons situated in the cerebral cortex. The primary motor area (M1; Brodmann area 4, BA4) integrates input from a range of both subcortical and cortical structures. This area is somatotopically organized, that is, there is a direct relation between a cortical region within this area and the body part it controls. The corresponding body part regions are situated alongside each other. The size of the cortical area (the number of cortical cells that are involved in the control of the body part) varies according to the level of fine motor control that is necessary to accurately use the body part. For instance, the fingers, involved in complex manual functioning, encompass a larger area than the upper leg. Other important cortical areas are the supplementary motor area (SMA, medial BA6, subserving simple motor tasks), the presupplementary motor area (pre-SMA, controlling complex motor tasks), and ventral and dorsal parts of the premotor cortex (PMC, lateral BA6; see Fig. 6.2). In addition, somatosensory areas are involved in the motor system as they contribute to the corticospinal tract that is essential for fine motor control of the hand (see for review Lemon 1993; 2008). This shows the tight connection between sensory input and motor output.

Fig. 6.2 The cortical areas involved in motor control. The primary motor cortex is Brodmann area (BA) 4. BA6 includes on the lateral side the premotor area and on the medial side the supplementary motor area (SMA). The supplementary eye field (SEF) is situated in BA8. Areas in the parietal cortex that contribute to motor control are the primary somatosensory cortex (S1, BA1, BA2, BA3a, and BA3b) and the superior part of the posterior parietal cortex (BA5 and BA7) (adapted from Gazzaniga et al. 2002)
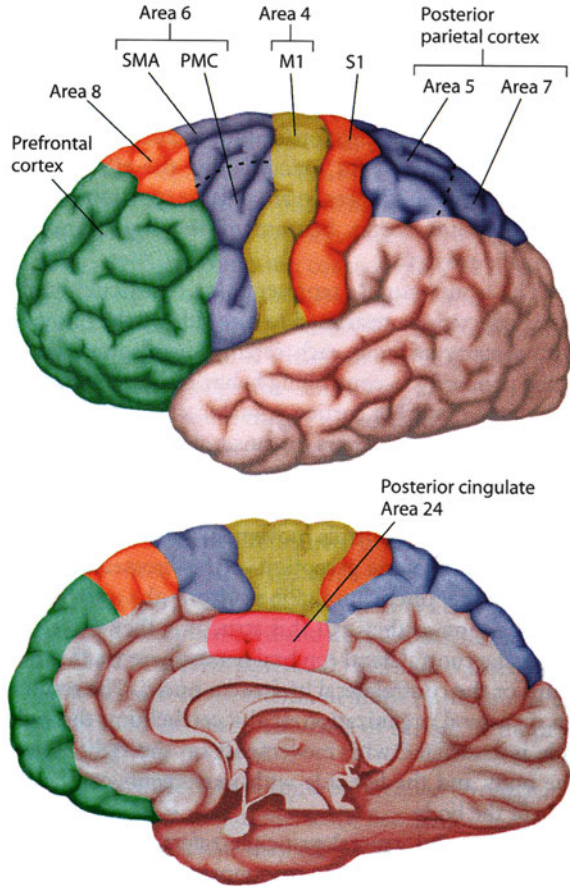
The primary motor cortex is the final stage for the execution of motor commands. They encompass an integration of signals, informative of the force and timing of the muscle contraction, that originate from the associative cortices, basal ganglia, and the lateral cerebellum (Cheney 1985). The motor commands "travel" through the corticospinal tract and finally activate the muscle via the (alpha) motor neurons that are located in the ventral part of the spinal cord and which connect to muscle fibers. At the same time, alpha motor neurons receive inputs from the tendons and the muscles that provide feedback information to the brain about the position and movement of the limb.

In voluntary movement, a plan must be formed about the action one is aiming to perform and the required action that needs to be selected to achieve the intended goal. This planning stage of movement involves activation of the highest levels of the motor system, that is, the prefrontal and premotor areas. Neural activities accompanying or immediately preceding the movement encode the direction, speed, and

other information. The premotor area receives input from the primary somatosensory area (BA1, BA2, BA3), posterior parietal cortex, and the cerebellum through the cerebello-thalamo-cortical loop. This loop enables cerebellar signals to modulate the motor cortex and its functions (Munzert et al. 2009). The posterior parietal cortex (both inferior and superior parts) is associated with various functions. It is, for example, involved in the integration of visual and tactile information and in the spatial construction of the world around us. In turn, these functions are crucial for the perception and recognition of one's own body (Dijkerman and de Haan 2007). The cerebellum is important for the coordination and timing of movement. It is activated both before and after the execution of movement. It has been suggested that the cerebellum is also involved in movement direction because timing is part of planning a specific movement trajectory (Ivry et al. 1988; Thach 1996).

To perform a selected action, the brain must execute a final motor command to the muscles. A copy of this action command (efference copy) is used to monitor whether it is executed as intended. It has been suggested that internal forward models of movement (forward dynamic models) are used to predict movement trajectories as well as somatosensory/kinematic consequences (forward sensory models), on the basis of the efference copy information (Wolpert 1997). Comparing the signals of the current state of the body part performing the action (position, time, velocity) with the efference copy of the motor command allows us to detect when a movement deviates from what was planned and control it accordingly. These internal forward models are also referred to as motor representations. They are continuously updated by new movement experiences, are thought to play a role in differentiating between what is "self" and what is "other," and are mediated by posterior parietal cortex (Blakemore and Sirigu 2003).

6.3   Motor Imagery: The Concepts

Motor mental imagery is studied by means of a variety of experimental paradigms. As the word "mental" already posits, it is hard to gain insight into the participant's strategy that is used to generate the required image. The process itself can therefore only be observed indirectly via behavioral (e.g., reaction times, task accuracy) or neural measures (e.g., fMRI or EEG). In addition, mental imagery questionnaires can be used to obtain insight into the participant's ability to perform the required imagery assignment. The use of such questionnaires will be further discussed in Chap. 14.

Both simple actions such as finger tapping (Hanakawa et al. 2003) as well as complex actions such as walking (Bakker et al. 2007), speed skating (Oishi et al. 2000), or playing tennis (Owen et al. 2006) have been studied (see Munzert et al. (2009) for a detailed overview of other types of imagery tasks). In these studies, participants are asked to actively evoke mental images (see Table 6.1 for imagery instruction examples). This is referred to as explicit imagery (de Lange et al. 2008). Motor imagery can also be evoked implicitly, for instance, when solving a

Table 6.1 Examples of MI scripts that were used to standardize the instructions (Lebon et al. 2008; Guillot et al. 2007; Lebon et al. 2012)

	Participants were instructed to imagine actions as follows
Lebon et al. (2008, p. 182)	"Try to imagine yourself performing the motor sequence with your eyes closed, by perceiving the different movements just as if you had a camera on your head, and feel the body's sensations. You have to see and feel only what you would see and feel if you had to perform this particular skill. Imagine the movement using the most comfortable way for you, and make sure not to move your arm"
Guillot et al. (2007, p. 3)	"Try to imagine yourself doing the motor sequence with your eyes closed by imagining the different movements, as if you had a camera on your head, and perceiving the body sensations. You see and feel only what you would if you actually performed this particular skill. Start the timer with your non-dominant hand, as soon as you have left the reference point (initial position), which means at the beginning of the first imagined movement. Imagine the entire sequence and stop the timer at the end of the contraction. Make sure you use imagery in the way that is most comfortable to you, but without moving your arm"
Lebon et al. (2012, p. 324)	"Now you are going to do an imagined condition. Close your eyes if it is more comfortable to focus on your right hand. Whenever you are ready, imagine the sequence of finger movements in the same order, and feel the contraction of the muscles involved in the movement and the contact between your fingertips as if you are actually doing the movement. When starting the imagery, press the switch in your left hand. Press it again as soon as you finish the final sequence"

hand laterality task (Parsons 1987). In such tasks, participants are asked to judge whether a depicted hand is a left or a right hand when they are presented rotated in different positions. It takes longer to judge pictures of hands that differ more from our own current hand position (larger rotations) than pictures of hands that are more alike this position. On basis of these observations, it has been suggested that motor imagery is used to mentally rotate one's own hand to see if it matches the presented picture, after which the left/right judgment is made. Other examples of implicit motor imagery are judging how to grasp a handle that is presented in various orientations (Johnson 2000) or judging the complexity of a certain movement (Frak et al. 2001).

In common everyday behavior, the different sensory modalities and the motor system are tightly linked. When interacting with our environment, we use visual information about items around us together with kinesthetic input about the configuration of our body for guiding our actions. Munzert et al. (2009) proposed that modalities are similarly linked in imagery activities. Imagery assignments need, therefore, to accurately direct the participant's attention to the required sensation or action. Several strategies can be used to evoke motor imagery, for instance, by

means of verbal scripts presented visually or in an audio stream. The imagery script needs to direct attention to the required sensation that must be mentally simulated. For motor imagery, this means that attention can be directed either to the visual or to the kinesthetic/somatosensory sensations of movement. For instance, the type of sensation that is emphasized most can be manipulated by instructing participants to imagine actions from a third-person or a first-person perspective (Munzert et al. 2009). The third-person perspective is as if you mentally see yourself perform the movement but from another person's point of view. This type of imagery relies mostly on visuospatial information of the action. In first-person-perspective imagery, it is as if you see yourself moving from your own point of view, for instance, as if you were wearing a head camera. Here, it is the sensation that your joints and muscles evoke that is emphasized, and this is often referred to as kinesthetic imagery. It has to be noted here that, in normal movement, kinesthetic sensations are tightly connected with tactile information perceived during active exploration of objects (Lederman and Klatzky 1987). If combined tactile and motor imagery creates a stronger mental image of motor action, through tight functional and neural sensorimotor connections, then establishing behavioral and neural effects of tactile imagery may be especially relevant. Although the similarity of the neural mechanisms underlying tactile mental imagery and tactile perception has been established earlier (e.g., Yoo et al. 2003), until recently it was unclear whether tactile imagery could affect tactile processing as is reflected in a behavioral response. Recently, Anema et al. (2012) showed that tactile imagery executed just before a short tactile stimulus on the fingers interfered with processing of the tactile information to a smaller extent as compared to auditory imagery (see Chap. 3 for more information on tactile and haptic imagery). However, the role of tactile imagery in motor/kinesthetic imagery remains to be investigated.

Mental imagery processes are affected by the participant's experience with the imagined content as well as with individual imagery ability. It is now well-known that the ability to voluntarily form vivid and accurate mental images of movements is not developed equally in all humans (for a discussion of motor imagery ability in neurological patients, see Chaps. 13 and 21). Vividness relates to the clarity and richness of the generated image, whereas accuracy can be expressed by the similarity between the mental content and reality. Paivio (1986) suggested that experience with imagery and genetic variability together make up a person's imagery ability. Certain studies specifically investigated individual differences (Hall 1985) and found them to be related to several variables such as perceptuo-motor ability and developmental stage (Isaac and Marks 1994). Differences in MI ability are important as it directly affects the degree of motor improvement when MI is used as mental practice to enhance motor performance (Guillot et al. 2008).

There are several different measures that can be used to assess motor imagery ability. The most widely used are questionnaires assessing the vividness of the motor image (see Chap. 14). Other measures include mental chronometry (e.g., the time it takes to imagine performing a movement, a close match to movement time for actually executing the movement suggests good motor imagery ability; Dijkerman et al. 2004; Guillot and Collet 2005b; Jeannerod and Decety 1995). Others have

used more implicit measures such as the hand laterality task (Williams et al. 2011) or a combination of questionnaires, mental chronometry, and psychophysiological concomitants of imagery (Collet et al. 2011).

It seems that the better the imagery ability, the more vivid the mental image and the greater the corticospinal excitability (Williams et al. 2011). In fact, it has been suggested that high-vivid participants create images that have closer resemblance to neural activation during perception as compared to low-vivid participants (Olivetti Belardinelli et al. 2009). Similarly, it can be assumed that the neural activation of high-vivid participants during motor imagery may have closer resemblance to real motor execution as compared to low-vivid participants. The vividness of motor imagery can be enhanced by focusing on (auditory and visual) sensory information during motor imagery (Ikeda et al. 2012). In turn, this leads to larger excitability of the primary motor cortex. A similar enhancement is observed when imagery is cued by external movement-related sensory stimuli (Heremans et al. 2009).

6.4   Similarities Between Motor Execution and Motor Imagery

6.4.1   Functional and Physiological Similarities Between ME and MI

As was described above, executing a movement and mentally imagining the same movement often involve similar behavioral and neural characteristics. Indeed, several psychophysical investigations have demonstrated that movement execution and simulation of movement have similar spatiotemporal characteristics and biomechanical constraints (e.g., Guillot and Collet 2005b; Maruff et al 1999; Papaxanthis et al. 2002). Moreover, motor imagery often follows the laws of movement control. For example, Fitts' law principles that apply to overt pointing movements can be similarly applied to imagined movement. When imagining pointing movements to small visual targets (a small square) as compared to large targets (large square), participants need more time to mentally simulate accurate pointing movements. This implies that, as for motor execution, the time required to imagine rapidly pointing toward a target is a function of the distance to and the size of the target. Such chronometric similarities have been frequently observed in various paradigms (e.g., Decety and Jeannerod 1996; Maruff et al. 1999; Caeyenberghs et al. 2009; Lorey et al. 2010).

Even when applying external manipulations such as attaching a weight to the arm, the duration of mentally simulated pointing movements correlated with that of executed movement (Papaxanthis et al. 2002; Gentili et al. 2004). This indicates that the brain is able to predict what this manipulation to the body means in terms of duration of a performed action and its somatosensory consequences. Thus, both inertial and gravitational constraints are accurately incorporated in the duration of the mental movement.

Motor performance is more accurate in the dominant hand as compared to the nondominant hand. That is, pointing movements by the dominant arm are executed with shorter movement duration and smaller errors. These motor asymmetries are similarly observed in mental imagery of movement. Besides common Fitts' law principles, Maruff et al. (1999) observed longer movement durations and larger errors associated with visually guided pointing movements executed with the nondominant hand in both real and mental pointing movements, although this effect was larger in the mental as compared to the real pointing condition.

The principles of Fitts' law in normal motor execution can already be observed at a very young age, even though the sensorimotor representations/internal models of movement are not fully developed. For imagined movement, however, Fitts' law only applies in older children. In a study by Caeyenberghs et al. (2009), children of several age groups ($N = 112$, 6–16 years old) were tested on motor imagery performance by using a computerized Virtual Radial Fitts Task (VRFT). The VRFT consists of pointing movements to five targets of various widths (2.5, 5, 10, 20, or 40 mm), which were positioned along radial axes from a central target circle. In contrast to Decety and Jeannerod (1996) and Jeannerod (1994), executed task performance was slower than imagined performance. Moreover, Fitts' law was applicable to executed movement performance at a very young age, whereas for motor imagery it was not. With increasing age, the correlation between imagined and executed movements became stronger. It is hypothesized that these age-related changes in MI reflect the children's emerging ability to purposely use internal models of movement and the subsequent effects in the external world for future actions, consistent with the gradual development of the feedforward control processes themselves (Caeyenberghs et al. 2009).

The ability to mentally perform movements also deteriorates with increasing age. Elderly (67 ± 4.5 years of age) adults seem to have less temporal correspondence between mental and real movement execution as compared to younger adults (24 ± 1.3 years of age; Personnier et al. 2010). This might be explained by the similar deterioration of the motor representations/internal models of movement in the elderly (Skoura et al. 2008).

Behavioral measures are not the only way to assess motor imagery. In a review, Decety and Jeannerod (1996) discussed the evidence that the extent of vegetative activation (i.e., activation of the autonomic nervous system that moderates heart rate increase, sweat secretion, and breathing frequency) should increase with the level of imagery effort that is employed during an imagery task. Indeed, heart rate and respiration increased during actual and mental locomotion in line with increasing speed (Decety et al. 1991). It was observed that the cardiopulmonary activation of mentally running 12 km/h correlated with an actual running speed of 5 km/h. Similar findings were reported with the mental simulation of swimming (Beyer et al. 1990), lifting dumbbells (Wang and Morgan 1992), and with exercising on a treadmill (Wuyam et al. 1995). These findings could not be explained by muscular co-contraction during the imagery assignment. Decety, therefore, concluded that central structures mediate the need for energy (metabolic demands) that is required for the planned movement to the same extent as for the actual execution of move-

ment. Similar autonomic nervous system (ANS) responses during motor imagery can be revealed by thermovascular effects such as skin blood flow and skin temperature and autonomic electrodermal effects such as skin conductance (resistance). Such effects have, for instance, been observed when mentally simulating swimming (Beyer et al. 1990) and a 500-m skating sprint (Oishi et al. 2000).

6.4.2 Muscle Activity During MI

Although mentally simulated actions follow the same rules and principles as motor executions and evoke autonomic responses that are normally seen during real action, a point of considerable discussion has been whether MI actually evokes muscle activity. In fact, lack of muscle activity, measured by means of electromyography (EMG) recorded at the skin, has long been used in neuroimaging studies to confirm that the brain activation was provoked by mental imagery of action and not by executed movements. Also, it has been hypothesized that subliminal EMG activity during imagined movements can be explained by a failure to generate purely mental actions (Personnier et al. 2010). However, evidence both for and against the hypothesis that MI generates muscle activity has been reported in studies using surface EMG recordings (see for an overview of the literature Guillot and Collet 2005a).

In an attempt to use the EMG signal in a more sensitive manner, Lebon et al. (2008) studied muscle activity during MI using EMG power spectrum frequency analysis. Measuring the median frequency of the power spectrum allowed the researchers to study specific muscle fiber activity, such as the conduction velocity of the motor neurons and the motor units' discharge frequency, during mental imagery and real execution of maximum voluntary contraction (MVC; elbow flexion). EMG was measured during mental imagery of concentric, eccentric, and isometric contractions and rest periods. The results showed that while the deviations in arm positions during rest and imagery tasks did not differ significantly, the EMG median frequency was significantly higher during actual movement (72.35 Hz) as compared to imagined movement (37.08 Hz) which in turn was significantly higher than at rest (33.18 Hz). Also, the median frequency was correlated with the type of contraction that the muscle produced, just as was observed in actual movement. The difference in the EMG signal between the rest and MI conditions was obviously not caused by actual arm movement. It seems that MI activates motor cortex to the extent that spinal motoneurons are recruited (Gandevia et al. 1997), albeit only weakly (Lebon et al. 2008).

Transcranial magnetic stimulation (TMS) is a method of modulating the extent of activity that travels "down" the neural system during motor imagery. TMS is applied directly to the skin surface of the skull. A rapidly changing magnetic field evokes weak electric currents that in turn cause depolarization or hyperpolarization in the cortical neurons. When applied to the motor cortex, it stimulates muscle contractions. These contractions are referred to as motor evoked potentials (MEP) which can be picked up on EMG (Barker et al. 1985). TMS of the motor cortex

during MI increases the amplitude of motor evoked potentials in muscles that are related to the imagined action compared to rest. The increased MEPs suggest that the corticospinal pathways are activated comparably to actual movement even though the MEPs are of lower amplitude than during actual movement (e.g., Fadiga et al. 1999; Clark et al. 2004).

In all, the above-mentioned studies suggest that at a functional level, motor imagery follows laws and principles that are common to motor execution. The same applies to effects of the autonomic nervous system revealed by cardiopulmonary activation and skin conduction. Whether MI actually evokes muscle contraction is still debated. It seems that the inhibition of actual motor commands during MI is not complete (Jeannerod 1994). The extent to which motor cortex is excited by imagery, and thus the subsequent motor-related activation (corticospinal pathways, muscles, and autonomic nerve system), seems to vary with imagery quality (Lebon et al. 2012) and with imagery ability (Williams et al. 2011). It may be that the activation of the corticospinal pathways and the muscles induced by motor imagery is related to imagery skill, that is, the more vivid the mental image, the more substantial the motor cortex activation and the larger the activation of the autonomic nerve system and muscles. Below, we outline the similarities and differences between motor imagery and motor execution at a neural level.

6.4.3   Neural Similarities Between ME and MI

Given the functional similarities between mental and actual movements, it seems plausible that both tasks are mediated by similar (sub)cortical structures. Indeed, it is commonly accepted that the neural circuits of motor imagery and motor execution partly overlap (Gerardin et al. 2000; Jeannerod 2001). However, the extent of the overlap may vary as a result of imagery ability (Olivetti Belardinelli et al. 2009). As described above, movement execution relies on a variety of cortical structures, such as the primary motor area (M1; BA4), the supplementary motor area and the premotor cortex (SMA, PMC, both BA6), parietal cortex including the somatosensory areas, and the cerebellum. Various studies have reported similar cortical and subcortical structures that are active during motor imagery. However, whether primary motor cortex is or is not activated is still debated (see Chap. 13 for a discussion on the involvement of M1 in motor imagery). Below, we discuss the evidence for the main neural substrates that are frequently observed to be active during motor imagery: for a meta-analysis, see Grèzes and Decety (2001), and for recent overviews of the literature, Lotze and Halsband (2006) and Munzert et al. (2009). Motor areas that have been found to be consistently active during MI are premotor cortex (PMC), supplementary motor area (SMA), and the parietal cortex. Premotor areas such as the dorsal part of the PMC, the dorsolateral prefrontal cortex in particular, and the inferior frontal and middle temporal gyri have been frequently reported to be activated during MI (Stephan et al. 1995). The ventral part of PMC, however, is less clearly related to MI activity (cf. Munzert et al. 2009). For the supplementary motor area (SMA),

it remains unclear whether the entire SMA or merely parts of it are activated during motor imagery (Deiber et al. 1996; Stephan et al. 1995). Pre-SMA has been found to be involved in working memory by holding information "online" which is subsequently used for action selection (Petit et al. 1998). Finally, posterior inferior and superior parietal cortices showed activation during motor imagery, with increasing activity related to increased spatial task demands (Wolbers et al. 2003). In particular, the anterior part of the superior parietal lobe revealed increased activation when imagined pointing movements required more accuracy (Lorey et al. 2010). The same increase in activation was observed in the anterior part of the cerebellum, the basal ganglia, and the putamen. Involvement in the cerebellum has been frequently reported in motor imagery tasks (e.g., Decety et al. 1990; Macuga and Frey 2011; Crémers et al. 2011). It is thought to be particularly active in mental simulation of unskilled movements (Chang et al. 2010) or in poor imagers (Guillot et al. 2008).

Based on TMS and EMG studies, it is likely that the primary motor cortex (M1) is also involved in motor imagery. However, this remains an ongoing topic of debate as inconsistent results have been reported so far in the functional imaging literature (de Lange et al. 2008). Several explanations, mostly of methodological origin, have been put forward to explain the inconsistency. First, Lotze and Zentgraf (2010) stated that primary cortex is not defined uniformly. Some use anatomical boundaries, while others use functional or cytoarchitectonic borders. In fMRI studies, the uncertainty of the borders is exacerbated during the normalization procedure. No two brains are alike: the size and structure of the brain differs substantially between participants. In order to compare the various participants' locations of brain structures that are active, the brain scans need to be normalized and grouped into a single, common spatial framework (e.g., Talaraich space: Talaraich and Tournoux 1988). This normalization process might lead to false attribution of areas (e.g., primary motor cortex) to neighboring structures. Second, Lotze and Halsband (2006) noted that studies that failed to observe activation in contralateral primary motor cortex (cM1) used fMRI, whereas studies that picked up activation in cM1 used magnetoencephalography (MEG) or (TMS) combined with EEG (cf. Lotze and Halsband 2006). Although fMRI has good spatial resolution, it has poor temporal resolution. According to these authors, it could well be that cM1 activity during MI, as compared to ME, is too short to be picked up by instruments with poor temporal resolution such as fMRI and positron emission tomography (PET). Third, simple motor images, such as flexion/extension movements of the fingers from a first-person perspective, might elicit more M1 activation compared to images of more complex activities from a third-person visual perspective.

Although of smaller activation as compared to executed action, M1 activation during motor imagery has been observed by a great number of studies using different tasks, different brain imaging methods, and in different populations (see for overview Muntzert et al., 2009). Nevertheless, M1 is not essential to perform motor imagery as a patient with an M1 lesion was able to perform motor imagery (Sirigu et al. 1995). Moreover, the difficulties experienced with real movement of the contralesional hand ("…the subjective impression of her fingers being glued together…" p. 1000) were also experienced during mental imagery of that hand's movements.

As M1 is the final relay station between cortical signals and signals descending to the periphery, motor imagery-related activity in M1 leads to the question where inhibition of the movement that is imagined, but not executed, takes place. It has been reported that specific networks within M1 prevent (inhibit) activity that leads to overt movement (Stinear et al. 2009; Kasess et al. 2008). In fact, prevention of a prepared voluntary movement involves a network of cortical and subcortical structures including the inferior frontal cortex (IFC), the basal ganglia, and the SMA and pre-SMA. In particular, a fronto-basal-ganglia network prevents descending motor commands by modulating the excitability of corticospinal and intracortical inhibitory neurons within M1 (Stinear et al. 2009; Kasess et al. 2008). High-resolution fMRI datasets analyzed with dynamic causal modeling revealed that SMA activity suppresses M1 during motor imagery (Kasess et al. 2008). It may be that a suprathreshold signal in M1 is suppressed, which is reflected in the absence of real motion, but subthreshold signals might leave M1 to influence spinal excitability which in turn causes subliminal muscular activation (Munzert et al. 2009).

As was described above, the more vivid the mental image, the more substantial the activation of the motor network (Olivetti Belardinelli et al. 2009) and the corticospinal pathway (Williams et al. 2011). Guillot and coauthors (2008) divided participants into good and poor imagers on the basis of autonomic nervous system responses (sweat secretion). Besides commonly activated structures, such as inferior and superior parietal lobules, premotor cortex, cerebellum, and putamen, it was observed that good imagers have more parietal and ventrolateral premotor activation than poor imagers. For poor imagers, mental imagery recruited the cerebellum and orbitofrontal and posterior cingulate cortices more than for good imagers.

6.5   A Comparison Between Imagery and Action Observation

M imagery is based on evoking motor representations. There are, however, several other ways to activate a motor representation. Perhaps the most well-studied is action observation. In the last 20 years, activation of motor representations through the mere observation of another person (or animal) performing an action has received considerable attention. This so-called mirror neuron system was first discovered in monkeys in the early 1990s (di Pellegrino et al. 1992). It has since been linked not only to motor control but also to language function and social cognition (Keysers and Gazzola 2009). In the literature, studies often discuss motor imagery and action observation as if they involve identical processes (Munzert et al. 2009). This is based on the action simulation idea of Jeannerod (2001), who suggests that they both involve internal rehearsal of actions without them being executed. However, the method of evoking the action representations is very different (top-down, internally generated vs. bottom-up, externally/visually activated). Several studies have compared the different ways of activating motor representations and have shown similarities as well as differences. This section provides a review of this literature.

Since the discovery of mirror neurons, there has been considerable attention for possible shared mechanisms between action execution and action observation, both at a behavioral and a neural level. Several studies have demonstrated the influence of action observation on motor performance. For example, Brass et al. (2000) showed reaction time (RT) facilitation when a finger movement was shown prior to performing a finger movement based on a symbolic or spatial cue. Furthermore, observation of actors learning how to move in a new environment can facilitate motor learning by the participant in a similar environment (Mattar and Gribble 2005). This new environment was created by using a robot arm that applied forces in a particular way to the actor's arm. Studies from the field of motor learning show that participants eventually adapt their movements in such a way that they take the external forces applied to their arm into account. The study by Mattar and Gribble (2005) showed that observation of the actors learning to move in the new motor environments allowed participants to learn the motor environment themselves better afterward but interfered with learning a different motor environment. Other studies showed interference of action observation when it coincided with execution of a different movement. This is the case when performing large sinusoidal arm movements (Kilner et al. 2003) and visually guided grasping movements (Dijkerman and Smit 2007). In the latter study, the maximum hand opening during grasping a standard object was enlarged when simultaneously observing an actor grasping a larger object.

Further evidence for the idea that action observation activates motor representations comes from neurophysiological studies. Several have shown that observing certain actions activates specific patterns of physiological responses that can be linked to actually performing those movements. Combinations of TMS over the motor cortex and EMG recordings are often used. In one of the first studies using such a paradigm, Fadiga et al. (1995) showed that during observation of visually guided grasping movements, TMS-induced motor evoked potentials (MEPs) were enhanced compared to control conditions. Subsequent studies showed that this selectivity was enhanced for observation of hand movements away from the body, which may correspond more to the position of the observer (Maeda et al. 2002). During grasping movements, the facilitation was greatest around the time of the maximum hand opening (Maeda et al. 2002; Gangitano et al. 2001). In another study by this group, participants observed grasping movements in which the hand closed unexpectedly (Gangitano et al. 2004). Here facilitation of MEPs following TMS was only found at the start of the observed movement, suggesting that action observation predicts the outcome of a motor action rather than an online matching and monitoring as the movement develops (Loporto et al. 2011). Furthermore, the effects are lateralized, in that facilitation of observed left hand actions is greater during TMS over the right hemisphere motor cortex and vice versa (Aziz-Zadeh et al. 2002). TMS may not only be used for modulating corticospinal excitability but may also modulate higher order processes prior to the activation of the descending motor pathways. This has been particularly used to assess whether the human premotor cortex is involved in the modulatory influence of action observation on action execution. Avenanti et al. (2007) used repetitive TMS (rTMS), a technique which

suppresses activation in the underlying cortical areas, over premotor cortex and primary somatosensory areas. Suppression of the premotor cortex reduced facilitatory effects of observing possible movements, while rTMS over primary somatosensory cortex (S1) produced such effects for observation of impossible movements (perhaps because the latter are related to larger sensory consequences). A recent study used paired-pulse TMS to investigate the ventral and dorsal part of the premotor cortex in action observation (Catmur et al. 2011). The first pulse was given over a section over the premotor cortex, followed by a second pulse of the primary motor cortex. As described above, previous studies have shown that action observation results in an enhancement of MEPs following TMS over the primary motor cortex. Catmur et al. (2011) observed that a pulse over either part of the premotor cortex increased this facilitatory effect of action observation on MEPs induced by a second TMS pulse over M1. This provides convincing evidence for a causal role of the premotor cortex in modulatory effects of action observation on corticospinal excitability.

The neural basis of action observation effects on motor control has perhaps been studied more widely using functional imaging. A search in PubMed on "action observation" and "fMRI" results in 101 hits (Feb 2012) and "mirror neuron" and "fMRI" had more than 200 hits, revealing how extensively this topic has been researched. It is not the aim of this chapter to provide an exhaustive overview of this literature. Rather we would like to review it in the context of similarities and differences with the neural processes underlying motor imagery. Overall, it is clear that action observation is associated with activity in a network of bilateral cortical and subcortical areas including parietal, temporal, and occipital visual areas and, particularly relevant here, two motor-related areas, premotor cortex and inferior parietal cortex (Buccino et al. 2001; Grèzes and Decety 2001; Rizzolatti et al. 1996; Rizzolatti and Craighero 2004; Chong et al. 2009; Dinstein et al. 2007; Molenberghs et al. 2011). These studies have shown that activation varies depending on first- vs. third-person perspective (Oosterhof et al. 2012) and type of movement made, either object-directed or meaningless gesture (Decety et al. 1997; Hétu et al. 2011). In addition Buccino et al. (2001) show a somatotopic representation in the premotor cortex. Overall, there seem to be considerable similarities in functional characteristics as well as underlying neural mechanisms between motor imagery and action observation. This would fit with the motor simulation hypothesis of Jeannerod (2001) that both action observation and motor imagery evoke an internal simulation of the action. Indeed, an early meta-analysis of functional imaging studies concluded that there is considerable overlap between action execution, simulation, and observation in the SMA, the dorsal premotor cortex, the supramarginal gyrus, and the superior parietal lobe (Grèzes and Decety 2001). However, they also reported some differences: motor imagery appears to also be associated with ventral premotor activation, while action observation uniquely activates temporal visual areas. Recently, more direct comparisons (e.g., within one study) between action observation and motor imagery have been made. A TMS study compared facilitatory effects of motor imagery, observation, and imitation (Clark et al. 2004). They observed greater effects of actual imitation, but no differences between imagery and

observation conditions. A recent neuroimaging study also compared imagery with action observation (Macuga and Frey 2011), but while they found extensive overlap in sensorimotor areas (including primary sensorimotor areas, premotor, pre-SMA, posterior parietal and superior temporal cortex), they also observed important differences (see Fig. 6.3). They suggested that the areas active during observation are a subset of those active during imagery, which in turn are a subset of those involved in imitation. Increased activation during imitation compared to imagery and observation was found in bilateral sensorimotor cortex, cerebellum, classic SMA, and parietal operculum (probably related to ascending and descending sensorimotor processing during execution). In the imagery condition, activation was enhanced compared to the observation condition for pre-SMA, cingulate, anterior insula, and left inferior frontal cortex. Only one area did not fit with this hierarchy, which was most posterior SMA, in which activation was higher for observation and imagery compared to imitation (see Fig. 6.3). Overall, this study may have important implications for the application of motor imagery and/or observation, suggesting that imagery may be more beneficial than observation for rehabilitation and brain-computer interface (see Chaps. 16 and 19).

6.6   Summary and Conclusions

This chapter aimed to provide an overview of the functional, physiological, and neural characteristics of motor imagery. The literature reviewed shows that motor imagery shares many characteristics with motor executions. This is the case when looking at behavioral characteristics but also when measuring physiological effects. Furthermore, functional imaging studies showed that imagining a movement activates a motor network that largely overlaps with that involved when actively performing a movement. The involvement of the primary motor cortex in motor imagery is still under debate, although the EMG/TMS studies do suggest that M1 is involved. The range of behavioral, physiological, and neural effects of motor imagery also overlaps with those reported during action observation. However, it is also clear that activation of a motor network through imagery or observation may be less extensive than during action execution, with observation perhaps providing the least activation.

Thus, the idea that motor imagery evokes similar motor representations as execution of movements seems to be well supported by a large number of studies using a range of different methodologies. This knowledge may be used in a range of different applications which will be discussed in other chapters. It is important for motor learning, as simulating movements evokes motor representations and thus increases motor learning. This is used in sport psychology (see Chap. 17) and rehabilitation of motor disorders (see Chap. 21). Furthermore, the clear and convincing evidence from neuroimaging and neurophysiological studies that motor imagery activates motor networks is currently used in brain-computer interfaces in which mental processes are used to interface with computers (see Chap. 22), which may be of great relevance to paralyzed patients.

Fig. 6.3 Results from a study by Macuga and Frey (2011) in which cortical activation during motor imagery, imitation, and action observation was compared. *Top*: activation in bilateral sensorimotor areas was larger during imitation than during observation. *Middle*: imagery resulted in larger activation in bilateral precentral and postcentral gyri, cerebellum, SMA, and insula, as well as subcortical structures such as putamen, thalamus, and basal ganglia compared to action observation. *Bottom*: observation vs. imitation only showed activation of caudalmost sector of SMA
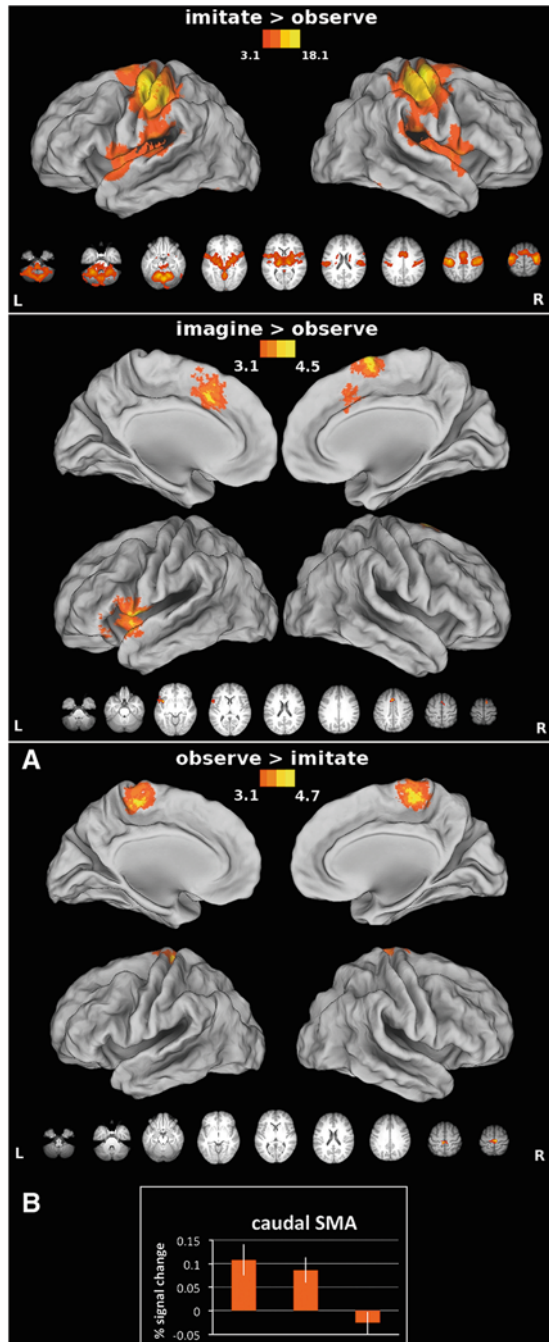
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Chapter 7
Mental Imagery and Blindness

Chiara Renzi, Zaira Cattaneo, Tomaso Vecchi, and Cesare Cornoldi

Abstract Although imagery is traditionally thought to be inherently linked to visual perception, growing evidence shows that mental images can arise also from nonvisual modalities. Paradigmatic in this respect is the case of individuals born blind or that became blind soon after birth. In this chapter, we will review evidence pertaining to different aspects of cognition showing that blind individuals are able to generate analogical mental images based on haptic or auditory input. These representations allow blind individuals to perform efficiently in a variety of domains which require the use of imagery (such as memory, spatial and navigation abilities, numerical cognition), though exhibiting in some cases specific limitations or differences, which likely depend on the modality in which information is usually acquired in these individuals (e.g., via haptics and hearing) and the particular strategies employed.

Keywords Imagery • Blindness • Spatial cognition • Visual impairment • Spatial biases • Navigation • Memory

C. Renzi (✉)
Department of Brain and Behavioral Sciences, University of Pavia,
Piazza Botta, 6, Pavia 27100, Italy
e-mail: chiara.renzi@unipv.it

Z. Cattaneo
Department of Psychology, University of Milano-Bicocca, Milan, Italy

Brain Connectivity Center, IRCCS Fondazione Mondino Pavia, Italy

T. Vecchi
Department of Brain and Behavioral Sciences, University of Pavia, Pavia, Italy

Brain Connectivity Center, IRCCS Fondazione Mondino Pavia, Italy

C. Cornoldi
Department of General Psychology, University of Padova, Padova, Italy

7.1 Can Blind Individuals Generate Mental Images?

Imagery is often regarded as a quasi-perceptual experience, and mental images can be built up from multiple sensory (e.g., visual, haptic, auditory) inputs (Halpern and Zatorre, 1999; Levy et al., 1999a, b; see also Chap. 8). Investigating mental imagery in blindness and visual impairment offers the unique opportunity to study whether, and to what extent, such ability depends on normal visual experience or can develop in the absence of visual input. As we will see in this chapter, imagery and its relation with different forms of perception have been widely investigated in congenitally/ early blind individuals (i.e., either born blind or that lost any visual capacity in the first days, weeks, or months of life; different studies being not always consistent regarding the definition of "early") and late-blind individuals (i.e., individuals that lost their visual capacity after childhood; see Cattaneo and Vecchi, 2011).

Although mental images do not necessarily rely on visual experience, in normally sighted individuals they are usually "vision-like," vision being the sensory modality we mainly rely on to explore and interact with our environment. As blind individuals cannot count on vision, the question arises as to whether their mental representations are purely "propositional" (i.e., based on abstract, semantic, language-mediated concepts) or are still analogical (even vision-like), although deriving from different sensory (haptic, auditory) inputs (see Chap. 1 for a brief account of the "imagery debates").

In the following paragraphs, we will review experimental findings suggesting that blind individuals robustly rely on mental images, although certain imagery processes may be more challenging in the absence of visual experience (cf. Pearson et al., 2008; Slotnick, 2008).

7.2 Mental Images and Memory Processes in Blind Individuals

There is evidence that—irrespective of visual experience—imagery, and not verbal processes, is critical for many memory processes, for example, those involved in learning or in the retrieval of autobiographical memories (Eardley and Pring, 2006). For instance, both sighted and blind individuals generate more autobiographical memories in response to high-imagery cue words than in response to low-imagery items, indicating that individuals born without sight do make use of sensory images (Eardley and Pring, 2006). Moreover, although early blind individuals tend to mainly refer to tactile, auditory, and spatial details in their spontaneous autobiographical memories (Ogden and Barker, 2001), they were found to generate an equal number of memories in response to visual, auditory, and tactile cue words (Eardley and Pring, 2006). These findings suggest that "visual" words have cross-modal connections to other sensory or emotional encoding of self-related experiences that allow privileged access to autobiographical memories compared to more abstract (low-imagery) cues (Eardley and Pring, 2006). Accordingly, during a

paired-associate task and a free-recall task with words varying in their modality-specific characteristics (such as color or sound, hence being highly visual or auditory), blind individuals performed as well as sighted participants with "visual-related" words and even outperformed the latter with "auditory-related" words (Zimler and Keenan, 1983). In studies concerning mental strategies useful to improve memory, it has been shown that blind children benefit from associating a pictorial-like mental format to information derived from haptically explored pictures, resembling the behavior of normally sighted children (Pring and Rusted, 1985). Consistent with these studies, no difference between blind and sighted individuals emerged in the use of mnemonic strategies involving mental images (De Beni and Cornoldi, 1985, 1988).

But how vivid are mental sensory images in the blind? In a series of experiments aiming to measure the vividness of mental images in blind individuals, Cornoldi and colleagues found that objects that cannot be experienced through touch received lower vividness ratings in blind individuals (Cornoldi et al., 1979; Tinti et al., 1999). In particular, high-imagery words whose referents can be experienced also through touch in the absence of visual experience (e.g., "cat") were rated similarly in their vividness by sighted and blind participants, whereas high-imagery words whose referents are hard to explore haptically (e.g., "palm tree") were rated higher by sighted volunteers (Cornoldi et al., 1979). This suggests that the dominant perceptual modality (i.e., touch in the blind) affects the way mental images are generated. These findings do not exclude that mental images in the blind can be characterized also by features that typically pertain to the visual modality. For instance, when asked to recall images of scenes, and a target object is described either as visible or concealed by another object, blind participants report more "visible" than "hidden" targets just as sighted individuals do (Zimler and Keenan, 1983).

Altogether, these studies suggest that blind individuals can generate mental images through different underlying sensory modalities. As in sighted individuals, these mental images are linked to memory representations involved in learning and in autobiographical retrieval.

7.3 Picture Recognition and Drawing Abilities

Three-dimensional (3D) objects require to be fractionated in a number of two-dimensional (2D) views in order to be pictorially represented (drawings being only two-dimensional), and this usually creates a selective difficulty in a congenitally blind person. In fact, blind individuals are familiar with touching 3D objects, but they are usually less familiar with converting 3D objects to 2D representations. Conversely, normally sighted individuals are continuously exposed to this kind of transformation: in fact, recognizing a picture means to link 2D (partial) views to a 3D object. As blind individuals are less familiar with the conversion of 3D space into 2D projections (Millar, 1975, 1991), the question arises as to whether they are able to recognize and produce 2D drawings.

Several studies suggest that visual experience is not necessary to recognize tangible pictures (Heller, 2006; for reviews, see Kennedy, 1993, 2006). For instance, in a picture-matching task where participants were asked to match a target picture with an identical one, congenitally blind individuals not only performed as accurately as blindfolded sighted participants, but they were even faster (Heller et al., 2002). However, although these findings suggest that blind individuals are able to extract the image of the haptically explored picture and to match it with a new percept, no actual identification of the picture nor matching to the real 3D representation is required in this task. In fact, identifying a 3D object by exploring a 2D model of it might be particularly difficult through haptics only. Both haptics and vision are equally able to deliver information about shape through contours and edges (D'Angiulli et al., 1998). However, the picture of an object may vary extremely depending on the particular viewpoint from which it is depicted. Haptic recognition of 3D objects is also sensitive to viewpoint (see Lacey et al., 2007; Lacey et al., 2009; Lawson, 2009; Newell et al., 2001), and blind individuals are therefore familiar with the "viewpoint" concept. However, recognizing 2D drawings when vantage points and perspective rules need to be taken into account was found to be particularly difficult for a blind person (see Heller, 2002; Heller et al., 2002, 2006). For instance, blind individuals perform as sighted individuals in drawing the top or sides of perceived shapes but encounter problems when asked to depict the object from a particular viewpoint (Heller et al., 2006) or when the shape is particularly complex (Heller et al., 2009). Similarly, blind individuals do not spontaneously apply perspective rules in their mental images. When required to point to imagined objects, early blind individuals do not take into account perspective (Arditi et al., 1988; Vanlierde and Wanet-Defalque, 2005; but see Kennedy, 1983). Moreover, when asked to produce raised-line drawings, early blind individuals do not spontaneously apply foreshortening (Heller et al., 1996). Nevertheless, blind individuals can learn to apply perspective rules in their mental representations when this is required (Dulin et al., 2008; Heller et al., 2002).

Importantly, blind individuals are able to produce vivid and rich mental representations, which can be translated into drawings and understood by a sighted person. Paradigmatic of this is the case of an early blind painter described by Amedi and colleagues (Amedi et al., 2008). Not only was this individual able to paint scenes that could be easily understood by a sighted person, but drawing was found to activate the blind painter's cortical regions typically involved in vision, including the primary and the secondary visual areas.

7.4 Blind Individuals and Spatial Mental Images

As specifically described in Chap. 8 by Loomis, Klatzky, and Giudice, spatial images are spatial representations that are generated and manipulated in working memory and that play a critical role in action control, spatial updating, and spatial navigation. Spatial images are inherently multisensory since they can be generated on the basis

of visual, auditory, and haptic stimulation but also by spatial language. Whereas the reader can find an exhaustive description of the properties of spatial images in Chap. 8, the following section aims to discuss some of the studies that investigated how spatial images are generated and manipulated by blind individuals.

7.4.1   Working Memory

Working memory (WM) tasks are commonly regarded as requiring the generation and processing of mental images (Baddeley, 2007; Cornoldi and Vecchi, 2000, 2003). A WM task typically involves both "passive" processes, such as the retention of a certain amount of information, and "active" processes that occur when the original input has to be somehow manipulated (e.g., rotated, combined with another object), giving rise to a new mental image (see Cornoldi and Vecchi, 2000, 2003). This passive-active continuum is also supported by neuroimaging findings, showing higher involvement of prefrontal areas in more active WM tasks, whereas sensory-related areas are mainly activated by passive storage of information (Smith and Jonides, 1999).

WM mechanisms have been extensively investigated in blind individuals. In a series of experiments, Cornoldi, Vecchi, and colleagues used a *matrix task* originally developed to study active and passive WM processes in sighted individuals (Kerr, 1987) to investigate the impact of blindness on these mechanisms (Cornoldi et al., 1993, 1991; Vecchi, 1998). In the active imagery condition of their experiments, early blind and blindfolded sighted participants had to haptically explore a matrix composed of wooden cubes and to generate the corresponding image in memory. They were then required to follow a pathway along the mental image, starting from a given point verbally indicated by the experimenter and following the experimenter's verbal sequential instructions (e.g., left/right, forward/backward). After following the instructions, they had to point on the real matrix to the square corresponding to the last position of the pathway (Cornoldi et al., 1991, 1993; Vecchi, 1998). To successfully carry out the task, participants have to build a mental image of the matrix and update it sequentially on the basis of the directions received, the complexity of the task varying with the size (3×3, 5×5, etc.), and the dimensionality of the matrix (2D or 3D). Results showed that early blind participants were able to generate a mental representation of the configuration but encountered greater difficulties compared to the sighted at increasing levels of complexity and especially in the case of 3D matrices (Cornoldi et al., 1991, 1993; Vecchi, 1998). It was hypothesized that the poor performance of the blind with 3D matrices could arise from problems in dealing with the simultaneous treatment of different spatial dimensions (vertical, horizontal, and depth) (Vecchi, 1998), but such interpretation has been questioned (see Eardley and Pring, 2007), as blind people have a greater experience with touching 3D objects than 2D images (Millar, 1975, 1991). It is hence possible that the lack of familiarity was the main critical factor in determining this pattern of results (see Eardley and Pring, 2007).

In the passive imagery condition of the matrix task, the surface of some cubes of the matrices was covered with sandpaper (thus making them highly recognizable by touch; Vecchi, 1998; Vecchi et al., 1995, 2004). Participants were asked to memorize the location of the target cubes after exploring the matrix with two hands. In the easiest condition, only one matrix was presented and had to be recalled. In a more demanding condition, targets were presented on two matrices and had to be recalled on two corresponding blank matrices or combined on a single blank response matrix. In the single matrix condition, the performance of blind and sighted individuals was comparable, even with high (eight targets) memory loads (Vecchi et al., 1995). However, when two different matrices had to be distinctly maintained in memory, the performance of blind participants dropped but only when targets had to be recalled on two blank matrices, whereas no difference emerged when only one response matrix was used (Vecchi et al., 2004). These findings suggest that the simultaneous retaining of multiple spatial images might be specifically affected in the absence of visual experience, due to the essentially sequential nature of haptic perception, on which blind individuals predominantly rely (Vecchi et al., 2004).

Blind individuals may compensate for their lack of "simultaneous" spatial experiences by relying on alternative encoding and memory strategies. For instance, Vanlierde and Wanet-Defalque (2004) required participants to haptically explore a 6×6 2D matrix and then listen to verbal instructions providing information about which positions were filled ("white" denoted empty cells and "black" filled ones; typical instructions were in the form: "first line: white, white, white, black, white, white; second line: black, etc."). In the recall phase, they had to indicate, according to a given grid axis, the filled-in squares contained in the matrix. Critically, the performance in early blind, late blind, and sighted groups was comparable. However, when interviewed about the strategies used to carry out the task, late blind and sighted participants reported mainly using a visual strategy while early blind reported using a verbal strategy in which target locations were memorized as pairs of "*X, Y*" coordinates on an imagined Cartesian axis. In a modified version of the "active" matrix task, Cornoldi and colleagues required sighted and blind participants either to recall the last position or the whole pathway (Cornoldi et al., 2009). The rate of correct responses was similar across groups for the "recall-the-last-position" condition (and notably, when articulatory suppression was added, similar marginal interference effects were observed in blind and sighted participants). However, sighted participants outperformed the blind in recalling the whole pathway. These differences likely depended on the different efficacy of the strategies used by blind and sighted individuals. Although overall the same main strategies—a spatial one (involving mental imagery), a verbal one, and a mixed one (spatial and verbal)— were used by both blind and sighted participants, the use of a pure spatial strategy was a poor choice for blind individuals (Cornoldi et al., 2009). Hence, when a task requires active mental manipulation, simultaneous processing, or continuous updating of a spatial representation, blind individuals tend to show specific deficits.

7.4.2   Mental Rotation

In a typical mental-rotation task, the participant is asked to indicate which of a series of shapes, visually or haptically explored, matches a target, with the correct choice being a rotated version of the target (Marmor and Zaback, 1976; Shepard and Metzler, 1971). In order to solve the task, one has to mentally rotate one of the two images. The usual finding is that response times linearly increase with the increase of the rotation angle, indicating that participants perform the mental rotation in an analogical way. Critically, this pattern has been reported also in blind individuals (Carpenter and Eisenberg, 1978; Marmor and Zaback, 1976; Röder et al., 1993), indicating that blindness does not prevent the employment of analogical mental representations. Nevertheless, in this task blind participants are usually significantly slower and make more errors compared to sighted controls (Hollins, 1986; Marmor and Zaback, 1976), suggesting once again that the use of analogical representations may be harder when vision is lacking. However, when taking into account the greater variability in the use of reference frame in the sighted, Hollins (1986) reported similar haptic mental-rotation functions in blind and sighted participants, so that initial differences in mental-rotation rates virtually disappeared.

7.4.3   Mental Scanning

In mental scanning paradigms, participants are required to mentally go from one point to another of an imagined scene, with reaction times typically depending on the distance to be computed, increasing with the increase in the distance between the two points (the so-called distance effect, see Kosslyn et al., 1978). This correlational pattern indicates that spatial mental images preserve the relative metric properties of the layout from which they have been generated, reflecting a structural isomorphism between the two representations. Critically, the distance effect has also been observed in congenitally blind individuals (Kerr, 1983; Röder and Rösler, 1998), again suggesting that blind individuals can make use of analogical representations, although the cost of generating and scanning these representations may be higher for blind individuals, as suggested by overall longer scanning times (Kerr, 1983). It is worth noticing that blind individuals' performance in scanning paradigms is affected by the size of the configuration to be mentally represented and, hence, by the way this configuration is learned (i.e., via direct haptic exploration or via locomotion). In particular, Afonso and colleagues (Afonso et al., 2010) found that permanent blindness did not prevent people from constructing representations in which metric information was validly represented and that congenitally blind individuals were even more efficient than blindfolded sighted ones in elaborating a metrically accurate mental representation of an environment learned by locomotion.

7.4.4   Spatial Updating and Navigation

Spatial updating is required to allow one to move and interact with the environment. For instance, in order to recognize a scene from a different viewpoint, one has to mentally rotate (spatially update) that scene before matching it with the original one stored in memory. This kind of operation requires efficient spatial imagery capacities. A series of studies by Jack Loomis and coworkers (Giudice et al., 2011; Loomis et al., 1993, 2002; see also Chap. 8) show similar updating performances of spatial images in blind and sighted individuals, consistent with the idea that changes in position or heading of the participant trigger the updating of the corresponding spatial image in working memory. However, blind individuals tend to rely on egocentric spatial representations using their body as reference, and this may lead to some limitations in spatial updating. For instance, Coluccia and colleagues (Coluccia et al., 2009) compared a group of congenitally blind and blindfolded sighted participants in a haptic task requiring recall of previously learned locations either from the same viewpoint (centered egocentric condition), from a 90-degree-rotated viewpoint (rotated egocentric condition), or from a different allocentric position. Results revealed that in both sighted and blind participants distance errors were higher in the allocentric and rotated conditions compared to the centered egocentric condition, but the blind made more distance errors than sighted participants in the allocentric condition. Overall, blind individuals seem to encounter specific difficulties when creating a mental representation of objects and/or scenes which are not related to their body. Heller (1989) argued that the spatial images of blind individuals differ from those of the sighted because the former lack experience of an external reference frame that contributes to the construction of object-centered representations (Heed and Röder, 2011; Heller, 1989; Rock and DiVita, 1987; Röder et al., 2007). In this regard, changes in viewpoint due to active locomotion seem to be particularly detrimental for blind individuals' memory. In a haptic object-location memory task, Pasqualotto and Newell (2007) asked a group of early blind, late blind, and sighted participants to indicate which object had changed position between study and test. In some trials, the object array was rotated by 45°, while in other trials the participants had to walk to a new position (again resulting in a 45° degree rotation). Although the rotation of the configuration affected memory performance in all participants, early blind participants were particularly impaired in the case of viewpoint changes due to locomotion (see also Ungar et al., 1995).

Spatial images are critical in navigation. In moving in the environment, one can rely on route-like or on survey-like representations (see Loomis et al., 1993). Route descriptions assume the point of view of a person who is moving within the environment; they are characterized by the use of an intrinsic frame of reference and egocentric terms, such as right, left, front, and back, and have a linear organization, given by the order in which landmarks appear along the route itself. Survey descriptions provide an overview of the spatial layout, sometimes with strong hierarchical organization; they are characterized by an extrinsic frame of reference and canonical terms such as north, south, east, and west (e.g., Taylor and Tversky, 1992). Therefore, survey representations put a strong load on the imagery

system (whereas "route representation" can also be easily verbally encoded). Several studies suggest that, unlike the sighted, blind individuals seem to rely more on route-like than on survey-like representations in route navigation tasks (Latini Corazzini et al., 2010; Loomis et al., 1993; Millar, 1994; Noordzij et al., 2006; Rieser et al., 1986; Steyvers and Kooijman, 2009), reflecting their overall preference for an egocentric type of representation.

Nevertheless, the spontaneous preference for route-like representations does not prevent the generation of survey-like representations in blind individuals, when the situation asks for it. In a study by Tinti et al. (2006), early blind, late blind, and blindfolded sighted participants were first required to walk on pathways of different complexities (as reflected by the number of turns involved) and then to perform a series of tasks which specifically implied the generation of a survey-like representation. In a first task, they had to find shortcuts by developing pathways which were not directly linked during the learning phase. In a second task, they were taken to random locations on the pathway and then asked to reach another place and to judge straight-line distances from these points. In a third task, participants were required to draw a map of the explored pathways. Crucially, during walking, participants performed backward counting to prevent the use of verbal strategies (i.e., a linguistic instead of a spatial representation of the pathway). Congenitally and late-blind individuals performed well in all tasks, even outperforming the sighted in some cases.

Tactile maps may be particularly useful in helping blind individuals to generate survey-like representations. In an experiment conducted to assess the effect of different instructions (direct experience vs. tactile map exploration vs. verbal description) on acquiring knowledge about a real unfamiliar space in a group of blind participants, brief exploration of a tactile map (but not a verbal description of the route) facilitated blind individuals' orientation and mobility in that environment (Espinosa et al., 1998). Tactile maps are useful because they include all relevant spatial information without the interference of noise and can offer an almost simultaneous view of the environment represented (Espinosa et al., 1998; Golledge, 1991; Ungar, 1997; Ungar et al., 1996, 1997, 1994): accordingly, tactile maps seem to represent a more suitable tool to convey survey-like representation rather than verbal descriptions, which might overload the WM system.

7.5 Numerical Cognition

Imagery abilities are also important for the way we represent magnitudes. In fact, several behavioral, neuropsychological, and neuroimaging data point to a critical role of visuospatial processes in the elaboration of numerical abilities (see De Hevia et al., 2008, for a review), and vision has been assumed to play a critical role in the emergence of numerical representations and abilities (e.g., Simon, 1997, 1999). In particular, there is evidence that humans tend to represent numerical magnitudes in a visuospatial format (Dehaene et al., 1993). This likely allows individuals to have access to an immediate representation of gross magnitude concepts, without each time assessing a more sophisticated calculation system. More specifically, numerical magnitude tends to be organized

along a left-to-right-oriented mental number line, with smaller numbers lying on the left of the line and larger numbers occupying the right portion (Dehaene et al., 1993). As a result, small numbers appear associated to the left hemispace and large numbers to the right one (Dehaene, 1992, 1993). Due to this spatial representation of numbers, numerical magnitude has been found to modulate attentional allocation to different portions of space. For instance, responses to small numbers are faster when they are assigned to left-button presses, whereas responses for large numbers are quicker if associated to right-button presses (Spatial-Numerical Association of Response Codes or SNARC effect; e.g., Dehaene, 1993). Similarly, when small numbers are presented as a cue, participants are faster to respond to stimuli in the left hemifield, while the opposite pattern holds for large numbers (Fischer et al., 2003, 2004).

Given the strong link between the way we represent numerical magnitudes and visuospatial mental imagery, some researchers have wondered whether lack of visual experience may influence the nature of number representations. A few studies have investigated this issue, and their results converge in suggesting that blind individuals also represent numerical magnitude in the form of a mental number line (Castronovo and Seron, 2007a, b; Cattaneo et al., 2010b, 2011a; Szucs and Csépe, 2005). For instance, in comparison and parity judgment tasks, early blind individuals exhibited both a "distance effect" (i.e., performance decreases as the numerical distance between the numbers to be compared decreases) and the SNARC effect (Castronovo and Seron, 2007b; Szucs and Csépe, 2005). Moreover, blind individuals also show the so-called size effect (Castronovo and Seron, 2007a), corresponding to a decrease in performance as numerical size increases (a finding that has been related to Weber's law: as numbers and quantities increase, the more their processing becomes approximate and imprecise; cf. Verguts and Van Opstal, 2005). Interestingly, the concurrent auditory presentation of numbers during a haptic line bisection task has been found to modulate the bisection performance in blind as well as in sighted individuals, with the presentation of small numbers inducing a leftward shift and the presentation of large numbers inducing a rightward shift in the original bisection bias (Cattaneo et al., 2010a). Despite these similarities, partially different processes may mediate this phenomenon, as suggested by an ERP study by Salillas et al. (2009). They reported that spatial attention shifts generated by the presentation of numbers are related to the modulation of different ERP components between the two populations: the N100 for the sighted and the P300 for the blind. As the former is usually regarded as a more perceptual component, while the latter is linked to more cognitive processes, it is possible that the blind process numerical spatial representations by means of working memory more than the sighted do.

7.6 Spatial Biases in Mental Spatial Representations

In a series of studies, Cattaneo and colleagues (2010a) investigated whether, and to what extent, the spatial biases and principles of spatial organization that characterize the representation of peripersonal space in sighted individuals are inherently related

to visual experience. Among the principles of spatial organization, bilateral mirror symmetry, and especially vertical symmetry, is extremely powerful. In a WM task where vertical or horizontal symmetry was introduced as an incidental feature, both congenitally blind and sighted subjects remembered more accurately configurations that were symmetrical compared to those that were not (Cattaneo et al., 2010a). Symmetry may thus represent a higher-order spatial representational feature that does not depend on visual features. However, whereas sighted subjects were aided more by vertical than horizontal symmetry, no such difference was found in the blind, thus suggesting that the perceptual salience of the vertical dimension is visually based.

Another bias typically shown in neurologically intact individuals is known as pseudoneglect and consists of a leftward bias in bisecting physical lines. When sighted and early blind participants were asked to haptically explore rods of different lengths and report their midpoint, all participants tended to bisect the rods to the left of the actual midpoint, consistently with the pseudoneglect phenomenon (Cattaneo et al., 2010a, 2011b). However, no bias was found for blind individuals when the task was performed in the vertical or in the radial plane, conditions in which sighted individuals typically show a downward and proximal (i.e., toward the participant's body) bias. Instead, for the early blind, the direction of the bias in these planes depended on the final movement direction during exploration, thus suggesting a role of different spatial reference frames to encode space and movement (Cattaneo et al., 2011b). Blind individuals also showed pseudoneglect in the bisection of numerical intervals (Cattaneo et al., 2011a). Overall, the consistent leftward bias shown by blind individuals in both line and numerical bisection suggests that the overestimation of the left side of space develops even in the absence of any visual input.

7.7   Conclusions

The findings reviewed in this chapter suggest that blind individuals can represent sensory information in an analogical format, but their imagery processes are affected by the modality by which they acquire the information (mainly haptically, through locomotion or from verbal descriptions), by the sector of space being represented (near/manipulatory space vs. far/locomotor space), as well as by exploratory strategies.

An impressive body of evidence shows that visual experience is not necessary to build up rich and vivid mental images nor to develop spatial navigation abilities and to perform spatial updating. However, the lack of sight produces differences and limitations, with respect to the sighted, in a series of imagery processes. For example, the absence of vision is more detrimental when a task involves "active" imagery processes, that is, when one has to actively operate on the generated mental representation by, for instance, updating (e.g., Cornoldi et al., 1991, 1993; Vecchi, 1998), scanning (e.g., Kerr, 1983), or rotating it (e.g., Marmor and Zaback, 1976).

Conversely, when only a passive retention of information is required, blind and sighted individuals perform more similarly (e.g., Vecchi et al., 1995). Very likely, the way blind individuals perform in different imagery tasks is linked to specific characteristics of their working memory system, which is highly affected by the nature of the perceptual input they experience (Cattaneo and Vecchi, 2008, 2011; Vecchi, 1998). In fact, haptic exploration (as well as auditory experience) is inherently sequential, and this might lead to a "piece-by-piece" construction of mental images. Thus, building up a representation "as a whole" likely requires a higher working memory load in blind individuals compared to sighted individuals, who may rely to a greater extent on parallel information processing (Cattaneo and Vecchi, 2008; Cornoldi et al., 1991, 1993; see also Pascual-Leone and Hamilton, 2001). In fact, when a task is relatively simple or can be solved by relying on verbally mediated strategies, blind individuals perform as well or even better than blindfolded participants (e.g., Vanlierde and Wanet-Defalque, 2004).

Moreover, some of the difficulties experienced by blind individuals in more active imagery tasks, such as mental rotation, may specifically depend on the smaller variability in the use of reference frames compared to sighted individuals (see Hollins, 1986). In fact, blind individuals may also experience limitations in tasks that do not critically involve WM, and this might reflect a qualitative difference in the adoption of spatial reference frames due to the lack of visual experience (Pasqualotto and Newell, 2007; Postma et al., 2007, 2008; Röder et al., 2008, 2007, 2004; Thinus-Blanc and Gaunet, 1997). Moreover, it should be considered that in many cases inefficient performance in blind individuals may reflect a higher interindividual variability rather than a true deficit (Hollins, 1986; Ungar, 2000). This points to the importance of always considering general cognitive abilities (e.g., verbal intelligence), educational opportunities (e.g., orientation and mobility courses, Braille-reading abilities), and other factors (e.g., gender, hand preference, blindness onset, and causes) in the sample recruitment and interpretation of results.

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Chapter 8
Representing 3D Space in Working Memory: Spatial Images from Vision, Hearing, Touch, and Language

Jack M. Loomis, Roberta L. Klatzky, and Nicholas A. Giudice

Abstract The chapter deals with a form of transient spatial representation referred to as a spatial image. Like a percept, it is externalized, scaled to the environment, and can appear in any direction about the observer. It transcends the concept of modality, as it can be based on inputs from the three spatial senses, from language, and from long-term memory. Evidence is presented that supports each of the claimed properties of the spatial image, showing that it is quite different from a visual image. Much of the evidence presented is based on spatial updating. A major concern is whether spatial images from different input modalities are functionally equivalent— that once instantiated in working memory, the spatial images from different modalities have the same functional characteristics with respect to subsequent processing, such as that involved in spatial updating. Going further, the research provides some evidence that spatial images are amodal (i.e., do not retain modality-specific features).

J.M. Loomis (✉)
Department of Psychological and Brain Sciences, University of California,
Santa Barbara, CA 93106, USA
e-mail: Jmloomis99@gmail.com

R.L. Klatzky
Department of Psychology, Carnegie-Mellon University,
Pittsburgh, PA 15213, USA

N.A. Giudice
Spatial Informatics Program: School of Computing and Information Science,
University of Maine, Orono, ME 04469, USA

8.1 Introduction

This chapter is concerned with what we call the "spatial image," a spatial representation that is relatively short-lived and, as such, resides within working memory. It plays an important role in the control of action in three-dimensional (3D) space when task-relevant perceptual information is no longer present (e.g., Tatler and Land 2011). Other researchers have used a wide variety of tasks, some dealing with action and others not, and different names to refer to the same or similar short-lived, action-related memory representations [e.g., egocentric model (Tatler and Land 2011), egocentric representation (Burgess 2008; Mou et al. 2004), sensorimotor location codes (May 2004; Kelly et al. 2007), spatial mental model (Taylor and Tversky 1992), and on-line transient representation (Waller and Hodgson 2006)]. All of these terms are meant to contrast with more enduring spatial representations in long-term memory (e.g., Amorim et al. 1997; Avraamides and Kelly 2008; Burgess 2006; Byrne et al. 2007; Easton and Sholl 1995; Huttenlocher et al. 1991; McNamara 2003; Mou et al. 2004; O'Keefe and Nadel 1978; Tolman 1948; Waller and Hodgson 2006; Wang and Spelke 2000). We have found it useful to refer to the underlying phenomenon as the spatial image, a term that is both more specialized and more evocative than the term "spatial representation."[1]

To give some idea of what we will be discussing, we ask the reader to engage in the following exercise, assisted by someone else. In your current location, look around and note three or four identifiable objects within a short walking distance. Close your eyes and begin walking forward. The other person will randomly choose which object is the goal and when you should turn. On command of the other person, turn toward the specified goal and walk a few steps in its direction. In opening your eyes, you can judge the accuracy with which you were spatially updating the location of the goal by noting how aligned your facing direction is with it. Similar exercises can be done with auditory targets and objects haptically sensed with a long pole. For most people, the spatial image representing the object locations is introspectively less vivid than visual imagery of familiar faces and familiar locations. In past research, we have used the term spatial image to refer to a single location (e.g., Loomis et al. 2002), but research indicates that the contents of spatial working memory can represent multiple point locations, simple paths, and oriented objects. Accordingly, we use spatial image to refer to the contents of spatial working memory, representing any of these possibilities. We hypothesize that even multiple surfaces, like those of a room, can be simultaneously represented in spatial working memory.

Our idea of the spatial image is closely connected to the more familiar idea of a percept (perceptual representation). Starting with the knowledge that perception

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[1]Röder and Rösler (1998) used the term "spatial image" in connection with the study of internal scanning of images from both vision and touch. Because their study focused on 2D maps, their use of the term seems to refer to a concept narrower than ours. Conversely, in their review of behavioral and neural research on mental imagery, Struiksma et al. (2009) use "spatial image" as a more encompassing term than we do.
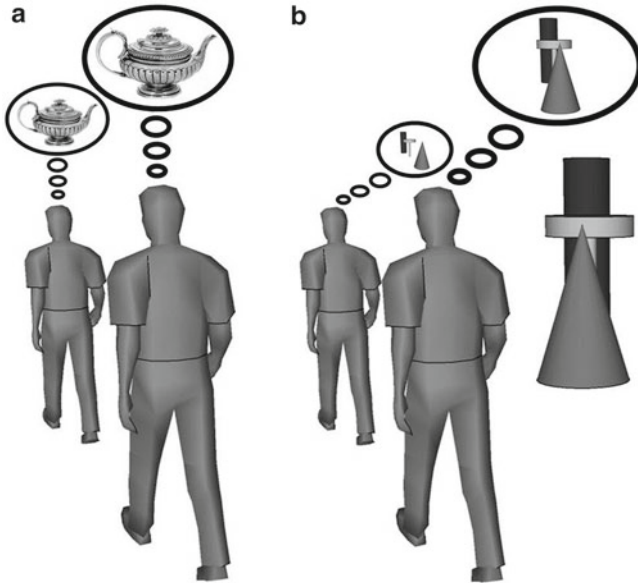
Fig. 8.1 Depiction of some differences between a visual image (**a**) and a spatial image (**b**). (**a**) As a person walks while imagining an object, the image remains more or less in front of the person and any changes in the visual image are not influenced by locomotion per se. (**b**) A person views a configuration of three objects and then closes the eyes. As the person then walks, the externalized spatial image of the objects corresponds spatially with percepts that would be there were the eyes still open. Accordingly, the objects represented within the spatial image vary in direction and exhibit parallax as the person walks forward

involves a causal chain involving sensory transduction, processing within the sensory pathway, and cortical brain activation, we accordingly adopt the view that the world we see, hear, and feel in everyday life is not the physical world itself but is instead a perceptual representation (e.g., Koch 2003; Lehar 2003; Loomis 1992; Russell 1948; Smythies 1994). For us, the percept and spatial image of object locations are similar representations in part because their referents appear external to the observer. Indeed, research supports the assumption that the spatial image produced by an external stimulus is spatially congruent with the resulting percept. Sometimes the perceptual location of an object is inaccurate with the result that the spatial image inherits this error (e.g., Philbeck et al. 1997).

We contrast the spatial image with a visual image that is depictive. This type of visual imagery is widely considered to retain properties of the visual percept such as color, texture, and shape; is picture-like in the sense of not exhibiting parallax; remains fixed within imaginal space as the person is walking or riding in a vehicle (Fig. 8.1a); and is experienced in the anterior half of the surrounding space. In our conception, the spatial image is experienced as external to the person's head and body and retains distance and direction information, such that as the observer spatially updates while translating, different components of the spatial image exhibit

relative parallax (Fig. 8.1b). In addition, the spatial image is not confined to anterior space but can exist in all directions around the observer, much in the way that auditory percepts do. More importantly, the spatial image is fundamentally multisensory in origin, for it can be instantiated in spatial working memory by visual, auditory, and haptic stimulation, as well as by spatial language. Whether spatial images retain features of the sensory modality from which they arose or are amodal in nature is a current topic of investigation. Finally, spatial images can be instantiated by recall of spatial layout from long-term memory. We present evidence for these claims in a subsequent section.

Our discussion has focused on differences between the spatial image and a depictive visual image, because theories of mental imagery have predominantly been concerned with the visual modality. However, as the present volume demonstrates, there is also interest in modality-specific imagery relating to hearing, touch, and movement. In distinguishing these from the spatial image, it is useful to consider three criteria put forward to demonstrate modality-specific imagery (Stevenson and Case 2005): (a) the subjective experience resembles the percept; (b) the effects of imagery in the modality mimic those of perception; (c) memory-based images can interact with perception in the modality. As we will make clear in the sections that follow, the spatial image can support behaviors that arise from perceptual sources, like spatial updating, and a spatial image recalled from memory can interact with one formed from perception. Thus, because criteria (b) and (c) can be met by both the spatial image and a modality-specific image that conveys information about spatial layout, they do not provide a means of distinguishing the two. However, the spatial image *is* distinguished by the fact that its content is not specifically modal; for example, a spatial image formed from hearing does not convey modality-specific content such as timbre. Spatial images can integrate inputs from multiple perceptual and cognitive channels; they transcend modality-specific features while retaining the spatial information shared by the inputs.

8.2   A Conceptual Framework

The functional block diagram in Fig. 8.2 provides a conceptual framework for spatial images and their transformation during spatial updating. The spatial modalities of vision, hearing, and touch, each encode stimulus information from one or more locations and output spatial percepts. For each modality, the spatial image is assumed to be spatially congruent with the percept within representational space, but of much lower precision and complexity. When the stimulus terminates, subsequently resulting in termination of the percept, the spatial image continues to exist for some short duration. Spatial images also can be instantiated within spatial working memory by way of inputs from spatial language and from long-term memory.

The lower part of the diagram shows the subsystem that provides input to the spatial updating process. Real rotations and translations of the observer result in the perception of self-motion, which, as the result of path integration, yields estimates
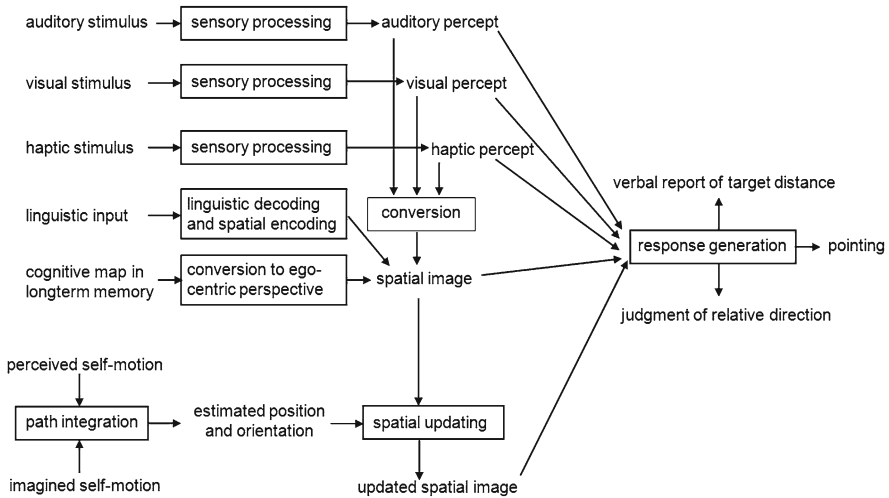
Fig. 8.2 Functional block diagram for the conceptual framework described in the text. Sensory inputs from vision, hearing, and touch give rise to percepts as well as spatially congruent spatial images. When the stimuli are removed, the percepts subsequently cease, but the spatial images remain. Spatial images can also be created by language and recalled from long-term memory. The lower section shows how both perceived and imagined self-motion can lead to a change in the observer's estimated position and orientation, which in turn can lead to spatial updating of the spatial image. The section on the right represents response generation. A wide variety of spatial judgments, several of which are shown, can be made on the basis of concurrent percepts or concurrent spatial images

of current position and orientation. The perception of self-motion is based on inputs such as optic flow, acoustic flow, inertial cues (e.g., vestibular), haptic cues, proprioceptive cues, and in the case of vehicular motion, feed-forward estimates of vehicular velocity based on an internal model of the dynamics of the vehicle (Loomis and Beall 2004). Another input to the path integration process is imagined self-motion, although it appears to be much weaker than perceived self-motion (Klatzky et al. 1998). The estimates of current position and orientation serve as input to the spatial updating process, which modifies the spatial image within spatial working memory (Byrne et al. 2007; Wiener et al. 2010). The updated spatial image provides estimates of the current locations and orientations of targets that were initially perceived. These estimates can be used to control locomotion relative to the targets. Not shown in the diagram are perceived changes in body posture during reaching and grasping that are signaled by proprioception and efference copy. These are involved in spatial updating at the scale of personal space.

The section of the diagram to the right deals with non-locomotor responses that can be executed based on percepts and/or spatial images. These responses include throwing balls at targets (perceived or updated), verbal estimates of distance and direction, and more complex judgments of the spatial layout of multiple targets, such as judgments of relative direction (JRDs).

8.3 Properties of the Spatial Image

8.3.1 Spatial Images Are Externalized like Percepts in 3D Representational Space

Like percepts from vision, hearing, and touch, spatial images are experienced as entities external to the head and body. This claim is supported by numerous spatial updating experiments in which the observer views an object location, closes the eyes, and then rotates and/or translates while mentally keeping track of the target's perceived location. Responses in such updating experiments include walking to the location of the updated target (e.g., Loomis et al. 1992; Philbeck and Loomis 1997; Rieser et al. 1990; Thomson 1983; Thompson et al. 2004), pointing toward it (e.g., Fukusima et al. 1997; Loomis et al. 1992; Riecke et al. 2005; Siegle et al. 2009), redirecting gaze toward it (Medendorp et al. 2003), throwing a beanbag (Sahm et al. 2005; Thomson 1983), walking and then gesturing with the hand (Ooi et al. 2001, 2006; Wu et al. 2004), and making a verbal report of its direction and distance (e.g., Klatzky et al. 2003). Auditory and haptic updating of single targets has also been demonstrated [e.g., audition (Ashmead et al. 1995; Loomis et al. 1998) and touch (Hollins and Kelley 1988)]. Figure 8.3 shows updating performance for visual and auditory targets situated 3 and 10 m away (Loomis et al. 1998). On some trials, observers walked directly to targets after viewing or hearing them, and on other trials, they were guided 5 m forward to a turn point, after which they walked unaided to the updated target locations. The near congruence of the centroids of the stopping points for direct and indirect paths for each target, especially for vision, indicates that updating is quite accurate for the average observer. The fact that the auditory responses were closer than the far targets and further than the near targets is consistent with the claim that the observers misperceived the distance of auditory targets and that the spatial image guiding the behavior inherited the perceptual error.

Figure 8.4 gives another example of spatial updating when perceptual errors are present (Ooi et al. 2001, 2006; Wu et al. 2004). In this case, when observers view a glowing target in an otherwise dark room, targets greater than 3 m away are perceived as closer but in the correct direction. When the target is positioned on the ground, the percept appears off the ground.

Most of the studies cited above involved updating a single target location, but research has also shown that people can update multiple target locations (e.g., Klatzky et al. 2003; Loarer and Savoyant 1991; Loomis et al. 1998; May 2004; Rieser 1989; Rieser and Rider 1991) as well as simple paths (e.g., Pham and Hicheur 2009). Figure 8.5 shows the mean walking trajectories from a fixed origin to oriented arrows on the ground plane, with visual guidance and without visual guidance following visual preview (Pham and Hicheur 2009). The figure indicates very similar walking trajectories with and without vision for three different targets. In another study, Loarer and Savoyant (1991) showed that after observers viewed several vertical columns at different distances and then walked with eyes closed,
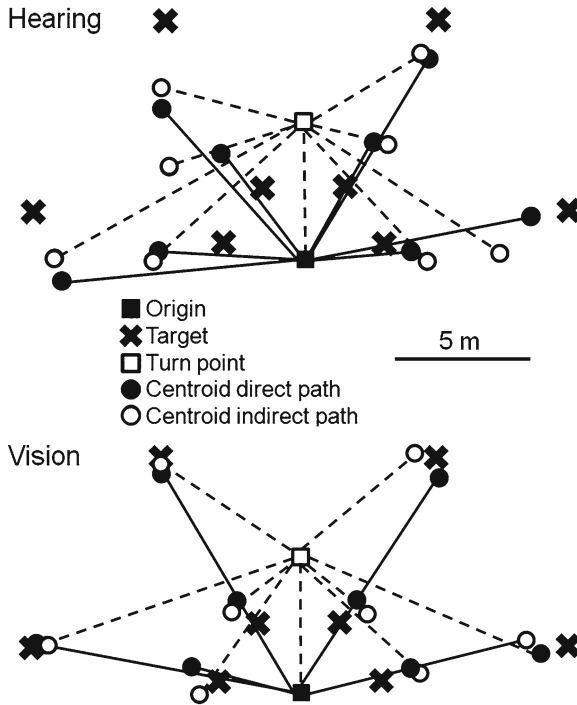
Fig. 8.3 Results of Experiment 3 of a study by Loomis et al. (1998). Observers were presented with auditory and visual targets at varying azimuths and at distances of either 3 or 10 m. On a given trial, after the target was presented, the observer attempted to walk without vision to its location either along a direct path or after being led forward 5 m to the turn point. The *open* and *closed circles* represent the centroids of the stopping points for the direct and indirect paths, respectively. The near congruence of the direct and indirect centroids indicates that spatial updating is quite accurate on average. Auditory targets were generally misperceived in distance, as indicated by the discrepancy between the target positions and the corresponding centroids. This is a modified version of Fig. 7 from Loomis et al. (1998) and is published here with permission of *Attention, Perception, & Psychophysics*

their responses indicated that the directional ordering of the columns changed as the observer approached, reflecting the parallax changes that would have been apparent were the eyes open. A similar conclusion is indicated by the results of Amorim et al. (1997), showing that observers are able to update both the location and orientation of an object.

Other experiments have shown updating with pure observer rotation (e.g., Farrell and Robertson 1998; May 2004; Presson and Montello 1994; Riecke et al. 2005; Rieser 1989; Waller and Hodgson 2006), but these are less diagnostic about external- ization of the spatial image than are translational tasks. With translation, the location of the updated spatial image changes in its direction during travel as a function of its distance, and updating research shows that the response is exquisitely sensitive to target distance. In contrast, observer rotation induces changes in direction that are
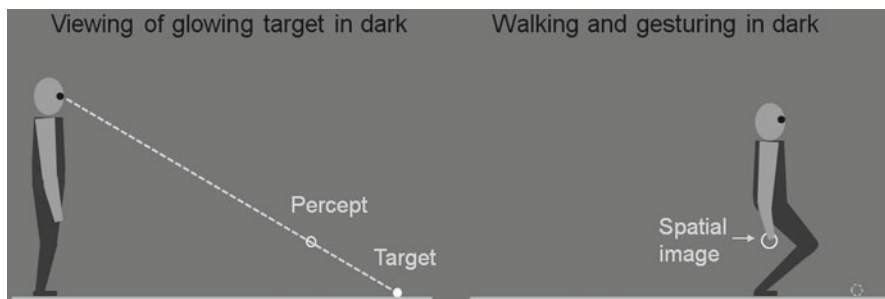
Fig. 8.4 Depiction of spatial updating of a target on the ground. When a dimly glowing target light is placed on the ground in a dark room more than 2 m away, it is perceived as closer than it actually is. Ooi et al. (2001, 2006; Wu et al., 2004) used a novel response in which the observer walked forward in the dark and then gestured with the hand to indicate the remembered location (spatial image) of the target. The results showed that the indicated location was closer than the target but along the same line of direction as viewed from the origin, indicating correct visual perception of direction but under-perception of distance. These results are consistent with a spatial image being formed at a location congruent with the percept and accurate updating of the spatial image during locomotion

independent of distance so rotational updating tasks are scale independent and can be performed more easily without an externalized spatial representation.

With many of the translational updating tasks involving a single target, there is an obvious alternative to the hypothesis of an externalized spatial image: execution of a preprogrammed action. The idea is that while viewing a target location or path to follow, an observer preprograms a motor response and upon closing the eyes executes the response. While some of the reported studies might involve this strategy, other experiments strongly support the hypothesis that observers update a spatial image by showing that observers can modify their actions in the midst of updating (e.g., Farrell and Thomson 1999; Fukusima et al. 1997; Loomis et al. 1998; Philbeck et al. 1997; Thomson 1983). To illustrate, we briefly describe the results of Fukusima et al. (1997), using a task similar to the exercise described at the beginning of the chapter. After viewing a single target, the observer walked along an oblique path; then, on instruction, turned and walked toward the target. Because performance was accurate even when a preprogrammed response was precluded by the observer's not knowing when the turn would occur, the hypothesis of updating with respect to an externalized spatial image is supported.

In theory, spatial images can arise from any activity that gives rise to a percept. Accordingly, beyond spatial images being associated with normal visual, auditory, and haptic perception, we would expect them to arise from specialized forms of perception like feeling targets with a cane or probe, echolocation based on reflected sound, and tactile and auditory substitution of vision. The most interesting cases are those in which perception based on short periods of sensing is followed by actions revealing perceptual localization of the targets, for it is in these cases that spatial working memory and putative spatial images are implicated. Bennett et al. (2011) conducted an experiment in which observers felt vertical poles of different heights
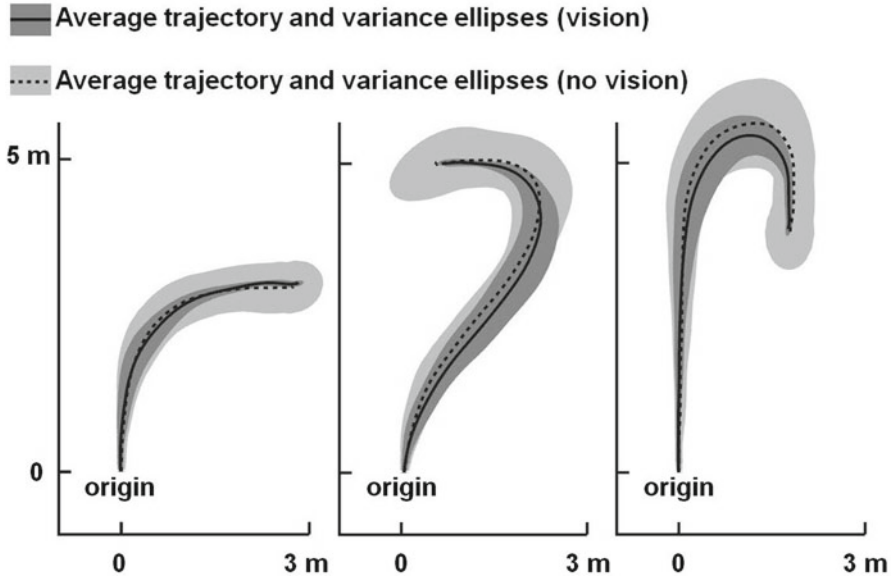
Fig. 8.5 Illustrative results from a study by Pham and Hicheur (2009) in which observers first viewed arrows placed on the ground plane at different distances and directions from the origin and then walked with or without vision so as to proceed along the length of the *arrow* (not depicted) and stop right at the tip of the *arrowhead*. The three panels show the responses to three of the many stimuli used. The average walking trajectories were very similar for the vision and no vision conditions. As expected, variability decreased in the vision condition as the observers neared the end of the *arrow*; whereas, variability remained high in the no vision condition. Other analyses showed that the velocity profiles were also very similar for the vision and no vision conditions. This figure is a modification of Fig. 3 from Pham and Hicheur (2009) and is published with permission of the American Physiological Society

at different distances and directions. Sensing was performed with extended touch using a 1-m probe, a 0.5-m probe, the bare hand, and vision, with the short probe and hand conditions requiring the observer to step forward to contact the target. Immediately afterward, the target was removed, and observers sidestepped from the origin and then moved forward and gestured with the hand to indicate its location. With this measurement procedure, which is based on triangulation, performance was very accurate in all four conditions, indicating mediation by an externalized spatial image corresponding to the target location.

There has been considerable research on echolocation and tactile and auditory substitution of vision, but the tasks employed so far allow for concurrent sensing of the targets while making judgments and thus are not dependent on spatial working memory [e.g., echolocation (Gordon and Rosenblum 2004; Hughes 2001; Teng et al. 2012) and sensory substitution (Auvray and Myin 2009; Chebat et al. 2011)]. Echolocation would, though, be another good way to test for localization mediated by a spatial image. For example, a large, reflecting target could be presented and the observer would sense its location using echolocation. After its removal, the observer would attempt to walk to its location.

8.3.2   Spatial Images Exist in All Directions

Unlike depictive visual images, which likely appear only in directions forward of the head, spatial images exist in all directions. Evolutionarily, this makes sense, for once a spatial image has been formed from visual input, if it is to be useful for action, it needs to continue to represent the same environmental locations despite rotations and translations of the head. Furthermore, because hearing and touch give rise to percepts in all directions about the head and body, the resulting spatial images must be omnidirectional. There is an abundance of evidence supporting the omnidirectionality of spatial images—a large number of studies show that people can update locations in all directions around the body during rotations and translations (e.g., Easton and Sholl 1995; Farrell and Robertson 1998; Giudice et al. 2011; Loomis et al. 1998; May 2004; Mou et al. 2004; Presson and Montello 1994; Riecke et al. 2005; Rieser 1989; Rieser et al. 1986; Waller and Hodgson 2006; Waller et al. 2002). With this evidence that spatial images exist and can be updated in all directions, a more interesting question is whether updating performance is better in front than behind. Horn and Loomis (2004) conducted an experiment to examine this question by comparing performance on a task in which the previously viewed target was either in front of or behind the observer during the updating phase. The observer viewed a target at one of various locations in an open field and then turned to face or face away from the target with eyes closed. The observer then sidestepped several meters and attempted to face the updated target. Two performance measures (mean signed angular error and within-observer variability) showed no reliable differences between updating in front and behind, and the third (mean absolute angular error) showed only slightly poorer performance behind (14.8° behind vs. 12.6° in front). This direct comparison of updating in front and behind shows that updating performance is performed well in both directions with minimal differences between them.

8.4   Functional Equivalence and Amodality

The above mentioned research indicates that spatial images based on visual, auditory, and haptic input can be updated. Other research has established that people can form spatial representations from linguistic descriptions of a scene and make spatial judgments similar to those produced while viewing or recalling that scene (e.g., Avraamides 2003; Avraamides and Kelly 2010; Bryant et al. 1992; Denis and Cocude 1989; De Vega and Rodrigo 2001; Franklin and Tversky 1990; Shelton and McNamara 2004; Struiksma et al. 2009; Taylor and Tversky 1992; Zwaan and Radvansky 1998). In a similar vein, Lyon and Gunzelmann (2011) found that visual depiction of movement along a 3D path conveyed with a first-person perspective and verbal description of movement along the same path resulted in nearly identical spatial judgments about the path. These research findings suggest that language can give rise to spatial images. Stronger evidence comes from experiments showing that spatial updating can be performed with respect to targets specified by language

(Klatzky et al. 2003; Loomis et al. 2002). Thus, the evidence supports the conceptual framework presented earlier (Fig. 8.2) in which the senses and language, all can give rise to spatial images (see also Bryant 1997).

A major part of the research done by our group has been concerned with whether the spatial images formed from vision, hearing, touch, and language exhibit "functional equivalence" (Loomis and Klatzky 2007). This refers to the hypothesis that once sensory or linguistic inputs are encoded as a spatial image, subsequent image-mediated behaviors depend only on the properties of that image, and not the source modality. Our research, described below, has demonstrated performance that is equivalent, or nearly so, across a range of spatial tasks involving different sensory modalities.

Assuming that functional equivalence holds, there are three interpretations in terms of underlying mechanisms (Giudice et al. 2011). The first of these, the separate-but-equal hypothesis, posits that equivalent spatial behavior across different inputs arises from modality-specific spatial representations that are isomorphic. Spatial isomorphism is not itself sufficient; what is further required are processes, either modality specific or modality general, that support equivalent processing outcomes. For example, there might be different mechanisms for calculating the Euclidean distance within auditory and visual representations, but if the representations are spatially isomorphic and the processes do not differ in accuracy, functional equivalence is guaranteed. A fundamental problem with this hypothesis, however, is that it suffers from a lack of explanatory power, as it offers no general principle by which modality-specific images would result in equivalent performance across modalities.

The second interpretation, the common-recoding hypothesis, postulates that inputs from multiple modalities are recoded into a single, modality-specific representational format. For example, all spatial inputs could be converted into 3D visual representations in memory (Newell et al. 2005).

The third interpretation, the amodal hypothesis, postulates that functional equivalence arises when information from all modalities converge onto a common spatial image that does not retain any modality-specific information (for a related term, metamodal, see Pascual-Leone and Hamilton 2001). Bryant (1997) proposed essentially this hypothesis with his idea of a spatial representation system (SRS), which provides a common format for the different input modalities of vision, hearing, touch, and language (see also Struiksma et al. 2009).

8.4.1 Evidence for Functional Equivalence in Spatial Updating

Spatial updating is a good way of testing for functional equivalence. In our work, we have shown near functional equivalence for updating tasks using combinations of vision, hearing, touch, and spatial language. In comparisons between different sensory modalities, especially with the goal of addressing functional equivalence, effort must be taken to match the perceptual representations by adjusting for known

sensory-specific encoding biases (e.g., Klatzky et al. 2003). For example, hearing often results in greater errors in distance perception compared to vision (e.g., Fig. 8.3). Failure to take this into account makes it difficult to interpret whether differences in test performance are due to differing perceptual errors during encoding or to fundamental differences in the spatial representation.

When we began this line of research, we wished to know if people could form a spatial image from a simple utterance specifying direction and distance, successfully update that image while walking, and perform with the same level of accuracy as with input from vision and hearing. This prediction was tested and supported in two studies (Klatzky et al. 2003; Loomis et al. 2002). In the 2002 study, locations were specified by language or hearing, after which observers immediately attempted to walk without vision to the specified location; in the 2003 study, observers learned multiple locations specified by vision, hearing, or language and later recalled one of the learned locations prior to walking to it without vision. We discuss only the latter study, because it adjusted for differences in distance encoding between vision, hearing, and language. There were two experiments, one involving the use of a pointer and verbal estimates to indicate the estimated target locations and the other involving blind walking to the estimated target locations. Because an analysis by Loomis and Philbeck (2008) showed that verbal reports are biased toward underestimation, we focus on the latter experiment.

Figure 8.6 gives the spatial layouts for the three modalities used in the experiment. The vision and language targets were at the same nominal locations, ranging in distance from 0.9 to 3.7 m. Because of the tendency for indoor auditory targets to be perceived as closer than they were physically, auditory stimuli were presented using loudspeakers placed at slightly larger distances, as shown, so as to produce perceptual locations close to those of the visual condition. In the learning phase, observers in the hearing condition heard synthetic speech labels (e.g., "baby," "horse") presented by the loudspeakers. In the language condition, observers heard synthetic speech giving the target coordinates followed by the label. In the vision condition, observers saw labels presented at eye level. Observers learned the target locations and then, when prompted with a label, attempted to report their directions and distances using a pointer and verbal report, respectively. The learning phase terminated when accuracy of both pointing and distance reports met stringent criteria. In the test phase, observers responded to each target label by walking either directly to the target or walking indirectly to the target after being passively guided to the turn point, either in front of or to the side of the origin. Of interest was the amount of updating error indicated by a difference in terminal locations for the direct and indirect paths.

Figure 8.6 gives the centroids of the terminal points for direct and indirect walks. The small separations between direct and indirect centroids in all six panels of Fig. 8.6 indicate that updating performance was good for all conditions. Language produced slightly larger updating errors than the two perceptual modalities, which did not reliably differ. The experiment demonstrated that spatial images can be formed from language as well as from auditory and visual perception, that spatial updating occurs for all modalities, and that the spatial images of vision and hearing exhibit functional equivalence in spatial updating, with those of language exhibiting near functional equivalence.
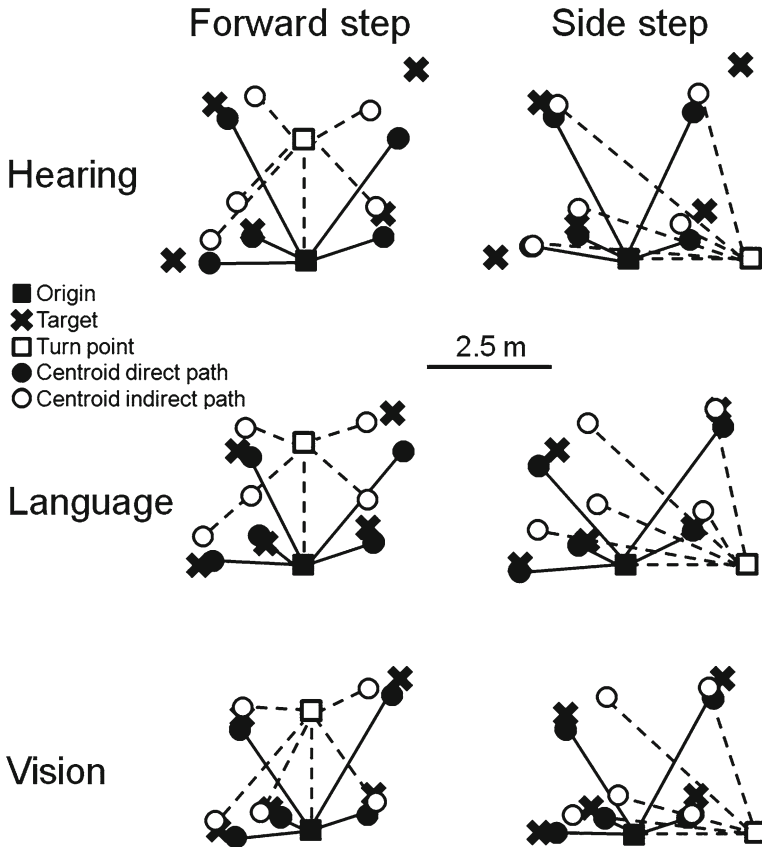
Fig. 8.6 Partial results of Experiment 2 of Klatzky et al. (2003). Observers were presented with targets specified by hearing, vision, or spatial language. The targets (X) varied in distance and direction. The auditory stimuli were placed further away to compensate for the expected under-perception of distance by hearing. Observers learned the locations of three or five targets. During testing, the observer recalled the location of a specified target and then attempted to walk without vision to its location, proceeding (1) along a direct path, (2) along an indirect path after being led forward 2.5 m, or (3) along an indirect path after being led 2.5 m to the right (sidestepping). The *open* and *closed circles* represent the centroids of the stopping points for the direct and indirect paths, respectively. The near congruence of the direct and indirect centroids indicates that spatial updating is quite accurate on average in all conditions. This figure is based on Figs. 4 and 5 from Klatzky et al. (2003) and is published here with the permission of *Experimental Brain Research*

8.4.2 Evidence for Functional Equivalence in Allocentric Judgments

The above studies evaluated functional equivalence in connection with egocentric judgments within the context of spatial updating, but the spatial image concept is by no means limited to that context. Another way to test for functional equivalence of spatial images is to examine patterns of error and response times in other forms

of spatial judgment. The study by Avraamides et al. (2004) evaluated functional equivalence of spatial images encoded from vision and spatial language, this time in connection with allocentric judgments in which observers indicated the relative distance and direction from one target to another. Observers learned indoor layouts of four targets in both vision and language conditions to an accuracy criterion. The allocentric reports then followed; on each trial, two targets were identified, and the observer reported the inter-target distance and direction. Distance was reported verbally, and direction was reported by aligning a pointer with the direction from one target to the other. Strong evidence of functional equivalence was obtained from the correlated patterns of response latencies, distance errors, and direction errors.

More recently, we investigated functional equivalence of spatial images built up from touch and vision between blind and sighted observers, this time at the scale of a table top (Giudice et al. 2011). Observers learned simple route maps (four points connected by three straight-line segments) by either seeing or feeling them. After learning, they performed judgments of relative direction (JRDs). These experiments exploited a well-known phenomenon in the spatial cognition literature known as the "alignment effect"—spatial representations are accessed more rapidly and more accurately when responses require imagining the environment from the same (aligned) orientation as at learning than from other (misaligned) orientations (e.g., Waller et al. 2002). The studies showed that alignment biases that have been commonly demonstrated for visual map learning (e.g., Levine et al. 1982) also occur with haptic map learning. Importantly, spatially updating the learned map in working memory while moving around it can induce a shift in the alignment effect, such that what was easy before movement becomes difficult after movement and vice versa (Harrison 2007; Waller et al. 2002). In the second experiment of this study, such a movement condition was included. Figure 8.7 shows the pattern of response errors in two of the conditions, rotation around the map and a "stay" condition in which the observer remained in the initial orientation. Alignment for the JRDs was defined not with respect to the learned perspective, but with respect to the spatial image in working memory, such that when the observer moved around to the opposite perspective view of the physical map, the perspective of the spatial image was correspondingly altered. The results in Fig. 8.7 clearly reveal a shift in the alignment effect for both touch and vision, confirming the results of Waller et al. (2002) using a different definition of alignment after movement. More importantly, response latencies and errors were remarkably similar for touch and vision over all twelve test conditions of the first two experiments, further confirming the pattern shown here for just four of the conditions and providing strong evidence for functional equivalence.

A third experiment replicated these findings with ten blind individuals, who performed the same task as the sighted observers but with haptic maps only. The results were like those of the haptic conditions with the sighted, demonstrating that (1) similar alignment biases occur with the blind, (2) accurate haptic updating is possible in this population, and (3) the equivalence shown in the previous work between haptic and visual learning cannot be attributed to recoding of the haptic information into a visual form. The highly similar pattern of results between modalities across all testing conditions and between blind and sighted observers
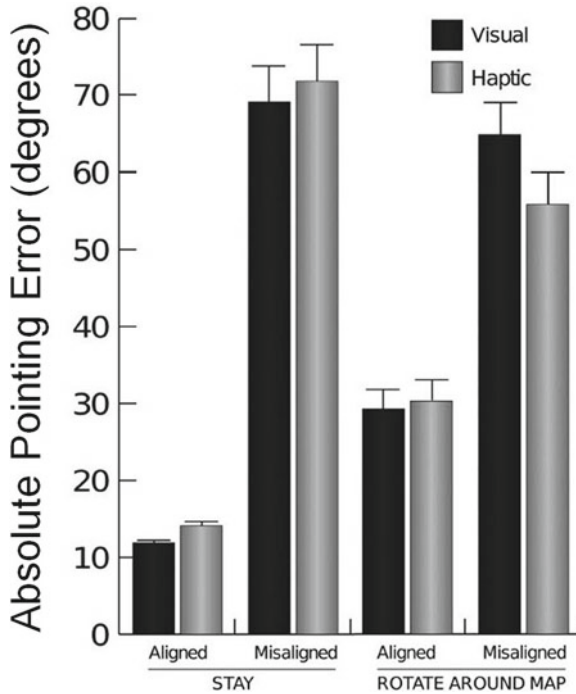
Fig. 8.7 Partial results of Experiment 2 in a study by Giudice et al. (2011). During the learning phase, observers viewed or felt maps with 3 linear segments. Their task was to remember the spatial layout of the four numbered vertices. During an intervening phase with eyes closed, observers remained in place (Stay) or walked around to the other side of the map (rotate around map). They were then to imagine standing at one vertex of the map (e.g., "2") facing another (e.g., "4") and then were asked to rotate physically to face a third vertex (e.g., "1" or "3"). Absolute pointing errors were very similar for touch and vision across the four conditions here as well as eight other conditions in this and another experiment, strongly supporting the claim of functional equivalence of spatial images derived from visual and haptic input. Note that aligned/misaligned in the rotate around map condition was defined with respect to the spatial image after rotation and not with respect to the learned perspective. Error bars are standard errors of the mean. This figure is a modification of Fig. 4 from Giudice et al. (2011) and is published here with permission of the American Psychological Association

supports the amodal hypothesis that information from all modalities converges onto a common spatial image that transcends any one spatial modality.

8.4.3   Evidence for Functional Equivalence in Learning Bimodal Layouts

We have postulated that functional equivalence is possible because people are acting on an amodal spatial image, but as discussed earlier, the common-recoding and separate-but-equal hypotheses are possible alternative explanations. The

equivalent performance of blind and sighted observers described above (Giudice et al. 2011) provides evidence against the recoding hypothesis. A further study (Giudice et al. 2009) specifically addressed the separate-but-equal hypothesis. This claims that different inputs lead to sensory-specific representations that are isomorphic, or nearly so, and that support similar behavior. Two experiments were conducted to investigate whether learning of interspersed haptic and visual object layouts build up into a unitary spatial image, independent of the encoding modality, or whether the individual input modalities are preserved in the ensuing representation. Bimodal and unimodal layouts were designed to be isomorphic; the question is whether there would be a cost of switching between the components of a bimodal spatial image, as would be expected from segregation by modality.

Observers were presented with a bimodal layout of six objects displayed on a circular platform that surrounded them. Half of the objects were felt and half were seen using a spatially congruent virtual environment. Importantly, in Experiment 1, the haptic and visual layouts were learned in isolation, whereas in Experiment 2, they were learned as a single interspersed layout. After learning all target locations to criterion, observers were tested on their ability to make judgments of relative direction between target pairs. As the critical manipulation, the two targets were either in the same modality (e.g., both visual) or a different modality (e.g., visual and haptic).

Results from Experiment 1, which temporally separated the haptic and visual objects during learning, showed clear non-equivalence. That is, trials where the start and end object came from different modalities produced responses that were significantly slower and less accurate than for pure visual or pure haptic trials. Thus, there was a switching cost for trials that require relating locations across two separate spatial images. These results suggest that temporal segregation of the layouts at learning led to distinct spatial images for the two modalities. By contrast, results from Experiment 2, where an integrated bimodal layout was learned, provide support for the formation and accessing of an amodal spatial image. Specifically, the response latencies and pointing errors did not differ between intra- and intermodal trials.

8.4.4   Summary of Research on Functional Equivalence

In this section, we have presented evidence from several tasks to demonstrate functional equivalence across input modalities. Strong similarities were demonstrated not only across the senses of vision, hearing, and touch but also the cognitively mediated modality of spatial language. What these inputs have in common is the space from which they originate. There is great efficiency in a cognitive architecture for which the same higher-level processes can be deployed, regardless of the input channel that is providing information about the surrounding space (Bryant 1997). The variety of tasks across which equivalence has been demonstrated should also be emphasized. They range from direct walking to targets to judgments of spatial

layout under assumptions of imagined movement. We have not only demonstrated that functional equivalence was the norm across multiple studies, paradigms, and observer groups, but our studies also presented evidence against competitors to the amodal hypothesis we favor, namely, separate isomorphic representations and common recoding.

8.5 Instantiating Spatial Images from Long-Term Memory

As mentioned in the Sect. 8.1, models of spatial representation commonly distinguish between short-term and long-term memory representations for spatial content (Amorim et al. 1997; Avraamides and Kelly 2008; Burgess 2006; Byrne et al. 2007; Easton and Sholl 1995; Huttenlocher et al. 1991; McNamara 2003; Mou et al. 2004; Waller and Hodgson 2006; Wang and Spelke 2000). Byrne et al. (2007) presented a computational model that traces bidirectional processing connections between the two forms of storage. Spatial learning corresponds to the transfer of perceptual information into a more enduring representation in the long-term store. Conversely, a layout retrieved from long-term memory can augment or complete a representation encoded perceptually into working memory, as long as the frames of reference can be co-registered.

Formation of a spatial image in working memory, suitable for spatial updating and derived from information in long-term memory, has been demonstrated in several studies. Rieser et al. (1994) found that children as young as 3 1/2 years could recall their classroom while at another location and then, while walking and turning, update the mental representation of the classroom as if they were there.

An important issue is whether the spatial image is degraded by storage in long-term memory. That long-term storage could introduce noise into the spatial image is indicated by studies showing a loss in precision of perceptual traces during memory storage (e.g., Amorim et al. 1997; Huttenlocher et al. 1991; Waller and Hodgson 2006). It is also possible that systematic bias might be introduced by storage in memory. Giudice et al. (in press) tested the effects of long-term storage in an experiment where composite spatial images were formed, combining locations retrieved from long-term memory with locations perceptually encoded from the same environment. The observer first learned a set of three targets (the LTM set), by viewing each one several times under dim illumination from a constant vantage point. The perceived locations of the targets were then measured by having the observer walk to each one without vision. The observer then left the room and took part in a mental rotation task intended to disrupt working memory. After returning to the room, the observers reported the locations of the LTM targets by a second round of blind walking. They then stepped sideways to a new vantage point, from which they learned three new targets (the WM set). Finally, the observers made judgments of relative direction (JRDs: imagine facing X, point to Z) involving two WM and two LTM targets or one WM and one LTM target.

The results indicated, first, that there was no shift in the reported positions of the LTM targets from the first to the second blind walking test. Thus, storage of the spatial image over a period of minutes did not produce systematic bias in the memory representation, and retrieval did not reimpose encoding biases. Second, in the JRD task, there was no effect of memory status (LTM vs. WM targets) on the time to make the judgments or on systematic error (which was, in any case, low). One effect of LTM storage was observed, however: The absolute error in the JRD task was greater, when the judged pair involved an LTM target, as compared to pairs with WM targets only. Similarly, pointing to single LTM targets showed greater absolute error than to WM targets. Thus, while memory storage neither added systematic bias nor precluded integration with targets recently encoded into working memory, it did apparently reduce the spatial precision of the remembered target location.

8.6 Memory-Load Demands on the Spatial Image

The spatial image, being one type of content within spatial working memory, is presumably subject to capacity limitations. A question of particular interest is whether this form of representation degrades as more locations are simultaneously represented. While several experiments have examined this issue, of necessity they measure the effects of memory load in the context of some other task, particularly spatial updating, which may by itself be subject to load effects. Given the resulting bias toward effects of memory demands, it is all the more impressive that the spatial image, at least within the context of spatial updating, appears to be unaffected by the number of locations stored within the range of 1–6, possibly more.

In general, the relevant experiments have a baseline condition with no updating and another in which observers translate, rotate, or both before responding. If there is no effect of memory load on the baseline condition, which can occur with small load or when targets are learned to a common criterion, the updating condition can be examined in isolation. Otherwise, a measure of updating error has been used; this subtracts the load effect in the baseline condition from the updating condition to assess the additional error attributable to updating per se.

In a study involving both adults and children, Rieser and Rider (1991) found no effect of the number of visual targets (1–5) on constant or variable errors in pointing without vision from a new location. In an fMRI study done using virtual reality, Wolbers et al. (2008) found that the error and latency effects attributable to updating over a simulated forward translation did not vary reliably over 1–4 targets. In a recently completed experiment by our group, observers walked without vision to the location of a target that had been previously viewed. Target locations ranged from 1.5 to 2.25 m in distance and varied in direction. During the observation interval, 1, 3, or 6 targets, identified by colored lights in a dimly lit room, were presented. During the response phase, observers began walking forward and were informed of the color of the goal target, at which time the observers turned and walked the rest

of the way to the goal target. The centroids of the individual stopping points were all close to the targets (mean of 14 cm). More important is the precision of the responses, represented by the variability of the stopping points from the corresponding centroids. For 1, 3, and 6 targets, the mean distances were 28, 26, and 30 cm, respectively, revealing little tendency for updating precision to decrease with number of targets. One study that did report an effect of memory load on performance in a study of updating in virtual reality with 1–3 target locations had procedural differences that make comparisons with other studies difficult (Wang et al. 2006).

Still larger numbers of targets have been investigated in updating tasks, with equivocal results. Harrison (2007) examined the effect of updating under rotations with 4–8 targets and found that set size affected pointing latency but not absolute error. Harrison's study was based on one by Hodgson and Waller (2006) with up to 15 targets. No memory-load effect on updating error after rotation was observed; however, this result was taken as evidence for a distinction between on-line and off-line spatial updating (Amorim et al. 1997). The argument is that as the spatial image becomes too complex, target locations are off-loaded to long-term memory. Updating then incorporates a process of memory retrieval as well as the change of egocentric coordinates with locomotion. An effect of number of stored locations was expected for on-line updating, under the assumption of limited spatial working memory, but no such effect was expected for off-line. However, the studies reported initially in this section suggest that effects of memory load on the spatial image, up to several locations, are not evidenced, even when on-line updating takes place. Beyond that point, the possibility of off-loading to long-term memory makes its capacity difficult to measure.

8.7 Are Spatial Images, as Considered Here, Synonymous with Classical Spatial Imagery?

In the voluminous literature on mental imagery, there is evidence of at least two distinct forms, visual imagery and spatial imagery, and their associated neural systems (e.g., Farah et al. 1988; Hegarty and Kozhevnikov 1999; Knauff 2009; Kozhevnikov et al. 2005, 2002; Mazard et al. 2004; Motes et al. 2008). Visual imagery retains visual features, such as color, is pictorial, and can contain lots of detail. Spatial imagery, in contrast, is coarse, more abstract, three-dimensional, and capable of representing objects undergoing motion. Some of the most compelling evidence for the distinction comes from recent research by Kozhevnikov and her colleagues (Blazhenkova and Kozhevnikov 2010; Blajenkova et al. 2006; Kozhevnikov et al. 2005); in their work, they focus on visualization ability and find support for two corresponding types of ability, object visualization and spatial visualization. The support consists of systematic differences in self-report, performance on different behavioral tasks, and psychometric evidence relating to choice of career (Blajenkova et al. 2006). Recently, Lacey et al. (2011) found that object and spatial dimensions of imagery can be observed in haptic and multisensory representations

as well. Clearly, the spatial image concept that is central to our chapter has affinities to spatial imagery and spatial visualization in the mental imagery literature. However, despite this, we are hesitant to identify spatial imagery in the classical sense with the spatial image as discussed here. Our focus has been a form of image that is externalized like a percept and scaled to the environment and, thus, can serve as a goal for action in space (see also Byrne et al. 2007). Spatial imagery in the classical sense, like visual imagery, can be manipulated through active imagination. Because it is less strongly tied to particular objects in the surrounding environment, it appears to have greater flexibility than the spatial image as defined here. Like visual imagery, spatial imagery as generally conceived can be imagined at different scales, in different directions, and can undergo rigid motion (Shepard and Metzler 1971).

8.8   Neural Substrate of the Spatial Image

Our theoretical model and the behavioral research we have described places clear constraints on the possible neural substrate of the spatial image: (a) It can be based on inputs from multiple sensory modalities, spatial language and long-term memory; (b) it represents space in egocentric coordinates; (c) it provides a basis (spatial updating) for guiding action when perceptual information is temporarily unavailable.

These features are generally consistent with the posterior parietal cortex (PPC), which has long been noted for its involvement in spatial attention and perceptually directed action (see Milner and Goodale 2008). PPC is multimodal; it has been characterized as an integration area for visual, somatosensory, auditory, and proprioceptive signals (Andersen 1997). Cognitively mediated spatial processes have also been implicated within PPC (Farah et al. 1988; Kosslyn and Thompson 2003). The PPC in primates is part of a network for transforming visual inputs into motor responses and likely plays a similar role in humans (e.g., Chang et al. 2009; Fernandez-Ruiz et al. 2007).

Byrne et al. (2007) have developed a neuro-computational model that satisfies most of the above constraints; in their work, they specifically pointed to the precuneus, the posterior medial portion of the parietal lobe (Cavanna and Trimble 2006), as a likely site for spatial working memory, which they call the *parietal window*. The content of the parietal window, which is synonymous with the spatial image, is described as a spatial map that is head-centered and egocentric and that represents the locations of visible landmarks and objects derived either from perception or memory. Their model contrasted the parietal window with the function of medial temporal areas, which provide an allocentric map.

Wolbers et al. (2008) specifically implicated the precuneus as the site for spatial updating. In their experiments using virtual reality, observers first learned the locations of one to four objects on the visual ground plane. In the delay phase that came next, observers experienced the objects as either remaining stationary (control condition) or moving forward visually, which elicited updating. After the delay phase, observers indicated the direction of the specified object. In the search for

candidate brain loci, the critical signature for updating was sensitivity to both the presence of translation and an effect of the number of objects. Only the precuneus fulfilled these requirements after ruling out activation due to spatial motor planning. However, the relative contributions of the PPC and MT areas to spatial updating continue to be a matter of ongoing discussion (Wiener et al. 2010).

8.9 Relevance for Assistive Technology for Blind People

A major challenge for blind people when navigating is a lack of access to information about the environment. When compensatory nonvisual information is provided about the environment, many of the challenges that spatial processing presents to the blind can be mitigated. For example, obstacle avoidance during travel and learning about the layout of objects within the nearby environment have long been facilitated by natural echolocation and the use of a long cane or dog guide. Improvement of these skills has been the goal of developers of ultrasonic obstacle avoiders, GPS-based navigation devices, and sensory substitution devices using tactile and auditory displays (e.g., Giudice and Legge 2008; Levesque 2009). The amodal spatial-image hypothesis that is supported by the work described in this chapter suggests that assistive technologies for the blind should build on capacities for spatial processing that blind people share with sighted people (Loomis et al. 2012). For reviews of research on spatial cognition in blind and sighted people, see Cattaneo and Vecchi (2011) and Struiksma et al. (2009).

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Chapter 9
Crossmodal Mental Imagery

Charles Spence and Ophelia Deroy

Abstract While researchers have long pondered over the nature (and even the very existence) of visual mental imagery, it is only in the last few decades or so that serious scientific research has been devoted to the study of this phenomenon in modalities other than vision. That said, the available empirical evidence now supports the view that mental imagery can occur in any sensory modality, though with widely varying degrees of vividness. It is at this point, then, that the question arises as to whether there might also be such a thing as crossmodal imagery. Crossmodal mental imagery has most commonly been reported under those conditions in which the presentation of a stimulus in one sensory modality results in the formation of a mental image in another modality. In this review, evidence supporting the existence of crossmodal mental imagery in neurologically normal adults is critically evaluated. Furthermore, similarities and differences with related phenomena such as crossmodal sensory forms of synaesthesia and crossmodal perceptual completion are also discussed.

Keywords Crossmodal mental imagery • Crossmodal perceptual completion • Crossmodal sensory synaesthesia

C. Spence (✉)
Crossmodal Research Laboratory, Department of Experimental Psychology,
University of Oxford, South Parks Road, Oxford OX1 3UD, UK
e-mail: charles.spence@psy.ox.ac.uk

O. Deroy
Centre for the Study of the Senses, Institute of Philosophy,
University of London, London, UK

9.1 Introduction

Imagine yourself watching someone talking on the television with the sound muted. Think about what your experience is like. If you are anything like our friends and colleagues, then you may well report that it "almost" feels like you can *hear* what is being said by the person you *see* talking on the screen, this despite the fact that there is no actual auditory speech stimulus present. Neuroimaging studies of this situation, that is, of silent lip-reading, have indeed demonstrated that the sight of active lip movements can induce a significant increase in auditory cortex activation, even in the absence of any auditory speech sounds (e.g. Calvert et al. 1997; Hertrich et al. 2011; Pekkola et al. 2005). Now, while the neural activation induced by silent lip-reading is certainly less pronounced than that seen when one is actually listening to someone else speak, its cortical distribution is actually quite similar to that observed when listening to auditory (or audiovisual) speech. The phenomenon of "silent speech" also has a number of interesting variants: So, for example, when you read the lyrics of a familiar song, you typically hear them sung or played in your head—that is, you do not read them like some unknown sentence, "pronounced" (so to say) neutrally (e.g. see Halpern 1992; Hubbard 2010; see also Abramson and Goldinger 1997).

It does not seem altogether far-fetched to wonder whether this phenomenon might not constitute an example of crossmodal mental imagery with, in this case, an *auditory* image being elicited by the presentation of *visual* stimuli. However, before evaluating the legitimacy of such a claim, let's take another example, this time from an experiment reported by Kitagawa and Igarashi (2005). These researchers made an audiovisual recording of the ear of an artificial dummy head being stroked by a brush. Crucially, the soundtrack was recorded by a microphone placed inside the ear of the dummy head. When this soundtrack was subsequently played back to participants over headphones while they were watching the video (see Fig. 9.1a), many of them reported that they felt as if their ears had actually been touched/tickled. Once again, though, these tactile experiences occurred in the absence of any physical stimulation of the participant's ear. That is, the participants were far more likely to agree (or at least were significantly less likely to disagree) with statements such as *I felt tickling on my own ear* and *I felt as if my own ear was touched* (see Fig. 9.1b).

Psychologists are, rightly, often sceptical of such self-report questionnaire data. There is, after all, always a danger that the results may reflect response bias—perhaps the participants concerned were simply trying to respond in the way in which they thought that the experimenter wanted them to (see Intons-Peterson 1983)—rather than reporting on their actual experience (e.g. as of being touched/tickled). Convincing evidence against an experimenter-expectancy effect account of Kitagawa and Igarashi's (2005) results might come from neuroimaging data documenting a correlation between subjective reports of tickling and increased activity in somatosensory cortex, say. Although such an experiment has yet to be conducted, the observation that participants' questionnaire responses were influenced when the soundtrack was presented over headphones (but not when it was presented from a
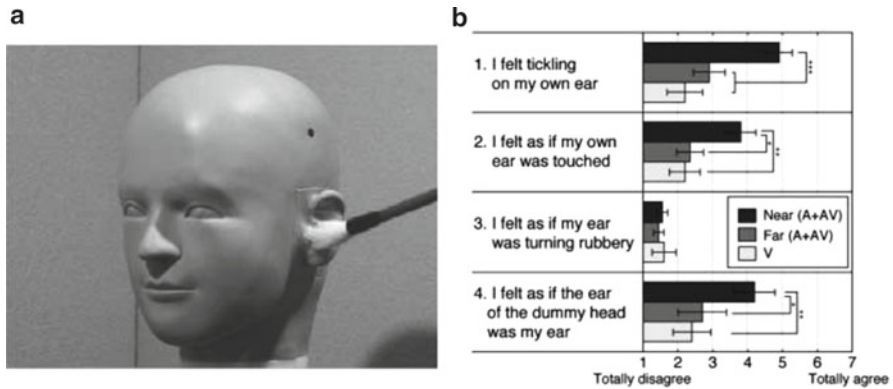
Fig. 9.1 (**a**) A frame from the video presented to the participants showing the left ear of the dummy head being stroked with a brush. A microphone was inserted into the left ear canal and recorded the sound of the brush strokes which were subsequently played back to participants. (**b**) Questionnaire results. Each bar indicates the mean rating of 20 participants (in the near and far conditions, when the sound was presented over headphones or from a loudspeaker placed 80 cm from the participant's head, respectively) or 10 participants (in the video-only condition (V)) with standard errors. Significance values are indicated with *asterisks* (*$p<0.1$; **$p<0.05$; ***$p<0.01$) (figure reprinted with permission from Kitagawa and Igarashi 2005)

loudspeaker placed 80 cm from the participant) argues against such an interpretation. Assuming, then, that Kitagawa and Igarashi's results are genuine, the question therefore arises once again as to whether or not it is appropriate to label it as another example of crossmodal mental imagery.

9.2   Distinguishing Crossmodal Mental Imagery from Multisensory Mental Imagery

An important preliminary question to be answered here though is whether, and why, one should use the term "crossmodal" in the first place. Indeed, given that some use the terms "crossmodal" and "multisensory" interchangeably, readers might wonder whether either term would do here when talking about mental imagery. We would like to argue that these two terms actually have quite different meanings (see also Stein et al. 2010). To be clear, in this chapter, the term "crossmodal" is used to refer to those situations in which the stimulation of, or experience in, one sensory modality influences the processing of stimuli presented in a different modality. By contrast, the term "multisensory" is typically used in the literature specifically to refer to those situations in which the stimulation presented in different modalities is combined in the representation of a single object or event having multiple sensory qualities (Spence and Bayne in press).

To us, the term "crossmodal" would therefore seem to be the more appropriate descriptor for what has been discussed thus far (i.e. for those situations in which the sensory input or experience in one modality elicits an experience in a different sensory modality). That said, the interested reader might wonder whether multisensory mental imagery also exists. Imagine for a moment having a face-to-face conversation with your best friend, or else imagine the flavour of a glass of your favourite wine. Intuitively at least, both of these examples would appear to involve multisensory imagery, audiovisual in the former case and olfactory plus gustatory (and maybe also visual and tactile—if you were also thinking of the sight and temperature of the wine) in the latter.

Unfortunately, however, things are by no means as simple as they might first appear. On the one hand, it is currently unclear whether complex sensory experiences, such as, for example, flavours might not represent a separate modality of sensory experience from gustation and olfaction (see Auvray and Spence 2008; Stevenson 2009a). On the other hand, it is also far from clear whether consciousness is ever truly multisensory in the sense of our being simultaneously aware of inputs from more than a single modality at any one instant. Indeed, the possibility has recently been raised that what appears introspectively to certain people as "multisensory consciousness" may instead reflect the rapid switching of their awareness between one modality of experience and another (see Spence and Bayne in press). According to the latter account, then, there might be no such thing as multisensory mental imagery after all—and the case of imagining your friend speaking in front of you might provide just such an example of the fast alternation between visually imagining the person's face and auditorily imagining the sound of his/her voice.

It would therefore appear that until such tricky debates have been resolved, it may be most appropriate to wait before jumping into any discussion of the psychological reality of multisensory (as opposed to, say, crossmodal) forms of mental imagery. Hence, in the remainder of this piece, we will continue to restrict ourselves to a discussion of crossmodal mental imagery.

9.3 Defining Crossmodal Mental Imagery

Although the authors of the two studies mentioned at the start of this piece never referred to their findings in this way (in fact, Calvert et al. 1997, make absolutely no mention of the subjective feelings/state of their participants while lying in the scanner), we would like to suggest that "silent speech" and "sound-induced touch" can indeed both be thought of as examples of crossmodal mental imagery. That is, of mental imagery occurring in one sensory modality as the result of the presentation of a physical stimulus in another (or possibly even of an imagined experience in that modality).

In order to further support the argument here, we need to furnish a relatively uncontroversial definition of mental imagery to work with. Some years ago, Kosslyn et al. (1995) provided just such a definition. According to these researchers: "Visual

mental imagery is 'seeing' in the absence of the appropriate immediate sensory input, auditory mental imagery is 'hearing' in the absence of the immediate sensory input, and so on. Imagery is distinct from perception, which is the registration of physically present stimuli" (Kosslyn et al. 1995, p. 1335). In other words, mental imagery can be defined as occurring whenever a person has a conscious sensory experience in the absence of the actual, corresponding sensory stimulation.

What exactly the nature of this experience is like has been at the centre of many debates—with some holding that mental images (at least, or especially, in the visual modality) are, in a sense, picture-like, as suggested by the very word "imagery" (e.g. Kosslyn 1994; Kosslyn et al. 2003), and others arguing strongly against such a view (e.g. Pylyshyn 1973, 2002, 2003; Ryle 1949; Sartre 1940; Slezak 1995). Thinking about the existence of crossmodal mental imagery in the various sensory modalities does, at the very least, seem to draw attention away from the controversies about "inner pictures." That said, it does not yet help to resolve the question about the nature of the experience—and how much its format resembles or differs from an actual perceptual experience. In fact, nothing that has been said thus far bears directly on the issue of whether mental imagery resembles an actual experience in the relevant modality.

Like Roger Shepard (1978), we are happy to agree on the minimal idea of a sort of correspondence between the mental image of an object and the perception of that object. However, where our definition of crossmodal mental imagery differs from previous thinking is that we would like to challenge the notion that this relation should be defined on a modality-by-modality basis. Indeed, a widespread assumption is that visual imagery is defined not only by the inner resemblance between the imagined experience and the visual experience but also by the fact that when triggered by sensory (as opposed to conceptual) input, it will be triggered by stimuli that are visual. As Shepard notes: "The relation of a mental image to its corresponding object is in some ways analogous to the relation of a lock to a key. (…) the lock can be externally operated only by its corresponding key" (Shepard 1978, p. 130)—that is, visual imagery can only be externally triggered by a visual object. And while we agree with Shepard that "It may also be possible to operate the lock, at least partially, by direct manipulation of its mechanism from the inside, in the absence of its external key" (Shepard 1978, p. 130), we also want to argue that the so-called lock can be externally operated by multiple sensory keys. In other words, our position is that the notion of a modality-specific external trigger for imagery has to be extended (see also Daselaar et al. 2010).

Returning to the examples of silent speech and sound-induced touch reported earlier, both are seemingly consistent with the definition of mental imagery provided by Kosslyn et al. (1995). The participants in Kitagawa and Igarashi's (2005) study, for example, consciously experienced tactile sensations that were described "as being like" those normally associated with having their ear touched; it's just that there was no corresponding (or appropriate) physical stimulation of their ear. Similarly, in the case of silent speech, people often report that they feel "as if" they can hear the person speak without there being any actual matching (or appropriate) auditory speech stream presented.

In both cases, people typically do not mix up their experiences (or concurrent sensations) with genuine percepts, again mirroring the situation in all but the most contrived of mental imagery research (e.g. Perky 1910; Sartre 1936; Segal and Gordon 1969; see also Sparks et al. 1995; Symons 1993). That is, when quizzed, people will normally prefix their statements in such experimental situations with qualificatory remarks such as *It is as if I can hear the speech* or *It almost feels as if I can feel the tickling of my ear.* This, though, deserves to be qualified: Although a mental image is experienced by most as less vivid (and accurate) than a perceptual experience, dividuals vary a lot with regard to the vividness of their mental imagery. These individual differences are even taken to be a key feature of imagery (e.g. Galton 1880c; Marks 1977; see also Eardley and Pring 2011; Zhang et al. 2004). Having now distinguished crossmodal mental imagery from the putative multisensory form, and having provided a general definition of what the phenomenon amounts to, we now turn to its further characteristics and first to the question of individual differences.

9.4 On the Vividness of (Crossmodal) Mental Imagery

It is worth noting at the outset that not everyone will necessarily experience crossmodally induced concurrents (or crossmodal mental images, as one might wish to call them in the quasi-pictorialist, or depictive, tradition of Kosslyn). (It is perhaps also worth noting that it seems easier to find examples, or at least candidates, in the literature for visual images being crossmodally induced than, say, auditory images generated by an olfactory stimulus.) However, this possibility shouldn't come as such a surprise given that profound individual differences in the vividness[1] of visual mental imagery have been a core feature of the phenomenon ever since researchers first started to investigate it more than a century ago (e.g. see Galton 1880a; James 1890, p. 57; Marks 1977; Reisberg et al. 2003). Putting aside the debates surrounding the validity of the assessment of these differences (e.g. Chara 1992; but see also Cui et al. 2007), the evidence that is now available would appear to suggest that such individual differences in vividness are just as (if not more) apparent when it comes to the study of modalities other than vision (e.g. Baddeley and Andrade 2000; Bensafi and Rouby 2007; Betts 1909; Djordjevic et al. 2004; Eardley and

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[1] It is legitimate to ask for a more precise definition of vividness. One might say that vividness refers to how rich and "reportable on" (e.g. how detailed) the image is (see Baddeley and Andrade 2000; Stevenson and Case 2005). However, according to an alternative view, it has been argued that the vividness of a mental image may actually correspond to how conscious one is of it. That is, the suggestion here is that we should treat vividness, or consciousness, as a continuous variable, rather than a discrete choice between something being either conscious or not (see Baars 1996, p. 262; though see Peirce 1935, vol. 6, §222 who argues that we need both vividness and what this vividness affects, i.e. a certain conscious quality or *quale*).

Pring 2011; Hubbard 2010; Marsella and Quijano 1974; Stevenson and Case 2005; see also Brower 1947).

An interesting question here, but one which has yet to receive an empirical answer, is whether individual differences in the vividness of unimodal mental imagery are correlated with differences in the vividness of crossmodal mental imagery. That is, will someone who reports vivid visual and/or auditory mental imagery also experience vivid crossmodally induced mental imagery (cf. Gilbert et al. 1998)? The limited neuroimaging data that has addressed this question to date is certainly not inconsistent with this idea (e.g. Daselaar et al. 2010; Olivetti Belardinelli et al. 2004, 2009).[2] That said, if one is of the opinion that crossmodal mental imagery is closely related to the phenomenon of synaesthesia (see below for a fuller discussion of this issue), then one might well doubt that this is the case. After all, very few of those individuals who report having a unimodal form of synaesthesia also report having a crossmodal form of the condition as well and *vice versa* (see Day 2005; Novich et al. 2011, for statistics). Given such observations, the prediction might be that the vividness of within modality (or unimodal) and crossmodal forms of mental imagery will not necessarily be correlated.

9.5   On the Internal Versus External Control of Mental Imagery

According to many researchers, mental imagery can either be triggered internally (i.e. volitionally) in the absence of any obvious external inducer (as when you suddenly decide to imagine how the inside of your last apartment looked) or can result from the presentation of a sensory trigger (as when the smell of a perfume suddenly brings back a vivid image of the face of an old flame). In Roger Shepard's (1978) terminology, the image can either be unlocked from the inside or operated from the outside, by the right key.

That said, it may of course be the case that many internally generated examples of mental imagery actually result from some external trigger; it is just that the triggering stimulus in question might not have been noticed/remembered by the individual

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[2] Olivetti Belardinelli et al. (2004, 2009) observed that higher associative areas located in the fusiform gyrus (BA 37) and inferior parietal lobule (BA 40) were activated when their participants were instructed to construct mental images based on sentences that they read. Additionally, putatively "modality-specific" cortical areas (see Ghazanfar and Schroeder 2006) also exhibited increased neural activity (e.g. gustatory cortex in response to gustatory imagery; see also Fallgatter et al. 1997). What is not yet known, but which seems at least intuitively plausible, is whether the common areas of neural activation simply reflect the common act of decoding the written sentences that participants were engaged in prior to eliciting a mental image in a particular sensory modality. The actual generation of the images (i.e. rather than the interpretation of the written instructions) then gave rise to patterns of neural activation that were more tightly linked to the relevant modality-specific cortical areas.

concerned (see also Segal 1971). The extension of mental imagery research to the crossmodal case is specifically relevant here, as it serves to extend the range of possible unnoticed stimuli, driving the occurrence of a certain image. Both introspection and scientific models (Roland and Gulyas 1994) also suggest that the simple presentation of an external stimulus is in-and-of-itself not (or at least not always) sufficient to trigger a specific mental imagery. In many cases, it would appear as though the external stimulus needs to be recognised—that is, some "internal" representation or process is needed before the mental image can be generated. So, for example, in the case of the sound-induced touch introduced earlier, it would seem necessary that the noise be identified as "the kind of sound that is heard when one's ear is actually stroked" in order for the effect to occur in the first place.

Similarly, in the case of silent speech, Campbell et al. (2001; see also Calvert et al. 1997) reported that while auditory cortex activation was present for silent speaking faces, it did not occur for face movements having a similar rhythm and duration, but which could not be construed as speech (i.e. when the seen face was engaged in gurning movements). Once again, such results are consistent with the claim that this sort of mental imagery is not merely stimulus-driven, but instead integrates various levels of stimulus categorization and identification. Similarly, when a participant is instructed by an experimenter to imagine a certain object "X," then to the extent that the participant does as he or she is told, it would seem as if this could be described as both externally (by the word uttered) and internally (by the interpretation of that word) generated mental imagery. Hence, given the above discussion, we would like to suggest that it may simply not be all that helpful to think in terms of whether a particular crossmodal mental image was generated strictly "from the outside" or from the inside; there is likely to be a continuum of possibilities here.

This said, it seems here that *some* of the internally driven cases will not be relevant to crossmodal imagery because they originate in thought or concepts (cf. the similar debate in the literature on synaesthesia; Hong and Blake 2008; Nikolic 2009; Simner 2007). Consider the case where I touch a cube, then come to think that there is a cube in front of me, and as a result form a mental visual image of a cube. The initial tactile determinant seems to play no role—at least as far as I could have also entertained the visual image because I was told to visually imagine a cube in front of me. In other words, as having a crossmodal induction is a definitional feature of crossmodal imagery, our definition excludes cases where the presence of a stimulus in another modality played no role in the induction of a mental image and only a contingent role in triggering a belief or conceptual representation. Distinguishing cases of crossmodal mental imagery from cases, such as the previous ones, where thoughts triggered by the presentation of a stimulus in one modality are uniquely responsible for the presence of the mental image in another modality might be difficult to draw in practice—although we contend that there should be ways of telling them apart, for instance, as imagery triggered by thoughts or concepts is more likely to be viewpoint-independent (in the sense that the particular view may not be important), whereas crossmodally induced mental imagery is more likely to be viewpoint-dependent (e.g. in the sense that, one needs to clearly see the facial movements that imply speech in silent speaking faces; but see Lacey and Sathian 2012, for a recent discussion concerning crossmodal shape recognition, as opposed to imagery, where the underlying representation is both

multisensory and viewpoint-independent). What is more, the distinction draws attention to some interesting cases: Even if there is a conceptual mediation, the triggered imagery could remain here crossmodal in an interesting sense if it owes something to the initial determinant in the other sensory modality. This case preserves the difference between the mental image triggered crossmodally and the other kind of imagery that one would expect if it had been generated in a strictly top-down manner. The difference in viewpoint dependence might be relevant here, but one might also think at this point of the old idea of "incorporation" put forward by Cheves Perky (1910). She demonstrated that while people normally imagine a banana as lying on its side, they would imagine it standing on its end vertically if a vertically oriented faint-yellow patch of light was presented on the black wall on which participants happened to be "projecting" their mental image. In that case, although it is conceptually driven and generated in a top-down way, the mental image "incorporates" some crucial elements of the present sensory determinant (though see also Segal and Gordon 1969).

Besides these cases where the initial sensory determinant of the thought or concept remains important, which we propose to call "crossmodally induced top-down mental imagery," there are two other kinds of cases where the crossmodality is central to the definition of the imagery process: First and foremost, the image in one sensory modality is directly triggered by stimulation in another modality, and this is a case of *immediate crossmodal imagery*; second, a kind of categorization of the inducer might be required to trigger the mental image in the other modality, but this categorization does not amount to a conceptual identification. Silent speech provides a good example of such a case, as the lip movements need to be recognised as speech-related movements (by contrast with, say, gurning movements) to induce an auditory activation and perhaps even as a general kind of phoneme to induce a more specific conscious concurrent. This form of categorisation is automatic and does not *require* any conceptual identification: If one accepts, for instance, the motor theory of speech perception (Liberman and Mattingly 1985), the visual stimulus triggers a motor copy of the lip movements, which in turn generates an auditory activation and, potentially, imagery episode, without any conceptual identification. In this sense, what we have here is a case of *mediate crossmodal imagery, different from conceptually mediated imagery*. Altogether, here we would like to argue that immediate, mediated, and crossmodally induced top-down imagery constitute three types of crossmodal imagery. A fourth possibility and an open question one might have—but one which is hard to test empirically—is to see whether there could also be some internal *crossmodal spreading of mental imagery*, that is, cases where a mental image in one modality (for instance, audition) triggers a mental image in a second modality (cf. Intons-Peterson 1992).[3]

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[3] Intons-Peterson (1992, p. 50) reports that people commonly report "seeing" mental images in addition to "hearing" them. She continues "In fact, for some stimuli, such as 'popcorn popping,' many participants said that they had to 'see' the popcorn popping before they 'heard' it!" Whether such reports can be taken as providing evidence of the existence of crossmodal mental imagery resulting from a mental image being generated in a different modality (i.e. rather than as the result of the physical stimulation of another modality) lies beyond the scope of this chapter. There may also be a fruitful connection to be made here to the literature on the spreading of attention across the various unisensory features of audiovisual object representations (see Busse et al. 2005; Fiebelkorn et al. 2010).

Interestingly now, all these three (or even four) cases of crossmodal mental imagery consider the phenomenon to be relatively automatic. What's more, and as we shall see below, it appears that this absence of control in the elicitation of a crossmodal image extends to the content of that image, which is largely then determined by the nature of the initial inducer.

9.6 On the Voluntary Control of Mental Imagery

Another feature common to many of the examples of mental imagery that one finds in the literature is that an individual has some degree of *voluntary* control over the contents of the mental image in question (again, and as we will see below, this contrasts with the case of synaesthesia). This control can either be expressed in terms of how vivid the image is (or, in the extreme, whether a conscious mental image is even experienced in the first place; cf. Baars 1996) or in terms of the ability that an individual has to manipulate (or transform, suppress, or, more minimally, inspect) the image once it has been generated (see also Stevenson and Case 2005). Indeed, it has been argued by some researchers that what distinguishes mental images from mere visual memories is the fact that while the former can be *manipulated* (or *transformed*), the latter can only be recalled (or maintained; see Kosslyn et al. 1995; Shepard and Cooper 1982; though see Galton 1880c, p. 324; Paivio 1971, 1986).

That said, the content of the crossmodal mental image does, in certain cases at least, seem to be *automatic* (in the sense of the content of the mental image being regularly and unavoidably related to the inducing stimulus). In the case of sound-induced touch, for instance, feelings of being stroked on one's ear were related to watching the audiovisual clip where the ear of the dummy head was being stroked. In reading lyrics, it seems very difficult to mentally hear them in any other way than "almost sung," that is, as being uttered in a neutral way. It seems then, at first, that many cases of crossmodal mental imagery will not allow the degree of freedom and control that is granted both by common sense and scientific definitions. However, it should also be borne in mind that a number of the best-known examples of mental imagery that have appeared in the scientific literature in recent times appear to constitute little more than particularly vivid visual memories (or to involve nothing more than the reactivation of an iconic or visual short-term memory representation; e.g. Finke and Kurtzman 1981; Ishai and Sagi 1995). Take, for example, a study by Finke and Kurtzman in which the participants were instructed to stare at an array of gratings for some minutes before having to try and hold them in imagery/memory while inspecting them visually. Finally, it is also important to remember here that there are more or less severe limitations on an individual's ability to transform (e.g. rotate) particular kinds of mental image. Such limitations could also be present in the case of crossmodal imagery.

Given the above, we would therefore like to argue that an ability to transform a mental image should not necessarily be taken as constituting a *definitional* feature of crossmodal mental imagery. Rather, what would appear to be common to the

majority of cases that commonly appear under the heading in the scientific literature is that the individuals concerned *feel* that they have the ability to exert some sort of voluntary control over the vividness (or duration) and/or, in some cases, the very elicitation of the mental image itself. In limited cases, they may also be able to transform their mental images in some way (e.g. by imagining mentally rotating a shape; see Shepard and Metzler 1971, or by "turning up" the loudness of the sound that is playing in one's head; see Intons-Peterson 1992), but that should not be taken as constitutive of mental imagery in general (no matter whether we happen to be talking about the unimodal or crossmodal variety).

9.7 Interim Summary

At this stage, it may be worth recapping where we have got to thus far. We have argued that crossmodal mental imagery can be said to occur under those conditions in which the presentation (or possibly even just the imagination) of a stimulus in one sensory modality elicits a mental image in another. We have identified four circumstances in which such a phenomenon could occur: Immediately, through categorical or conceptual (incorporated) mediation, and finally, through a form of crossmodal spreading of mental imagery. It has also been suggested that given the extensive literature that has been published on the topic of mental imagery within a single sensory modality, it is likely that there will be large individual differences in the vividness of crossmodal mental imagery. We have also attempted to distinguish between crossmodal and multisensory forms of mental imagery. Given several tricky philosophical problems (and more prosaically, a shortage of words on our part), we have chosen to focus solely on the former here.

Part of the definition of these phenomena certainly needs to go further than a common causal origin and extend to a functional characterisation. Here, then, we need to introduce a couple of other examples of crossmodal mental imagery in order to address this latter issue. Our purpose in introducing these new cases will be to try and highlight an apparent functional distinction between the two seemingly different forms of crossmodal imagery: One that comes close to a form of crossmodal perceptual completion and the other which appears more like the strategic generation of mental imagery in one modality in order to help determine the identity of a stimulus physically presented to another.

9.8 Crossmodal Mental Imagery and Crossmodal Perceptual Completion

Returning to the two examples with which we started this piece, silent speech and sound-induced touch, it is worth noting that in both cases, the concurrent experience (or mental image) seems to be closely linked to the recognition of the inducing

sensory stimulus. That is, what is being imagined is certain of the sensory attributes of a complex multisensory object or event that just so happens not to be physically present to perception in its entirety. More specifically, the perception of this complex object is limited to fewer senses than are usually involved under typical stimulation conditions (auditory and tactile stimulation, respectively, are missing in the cases of silent speech and sound-induced touch mentioned earlier). Under such conditions, it almost seems as though what we have heretofore labelled *crossmodal mental imagery* could plausibly also be described as a form of crossmodal *perceptual completion* instead.

Now, many people will be familiar with the phenomenon of perceptual completion in the visual modality (see Fig. 9.2a, b for a couple of famous examples). In recent years, a number of examples of perceptual completion have been demonstrated in other senses as well (e.g. Fig. 9.2c; see also Carlyon et al. 2002; Spence 2011; Kitagawa et al. 2009; O'Callaghan 2008; Warren 1970). Regardless of the sensory modality in which it occurs, perceptual completion is typically defined as the filling-in of the missing features of a stimulus that is physically present (e.g. Gallace and Spence 2011; Pessoa and De Weerd 2003).

Now while it may well turn out to be that all of the cases of perceptual completion that have been reported in the literature to date have been of the *unimodal or amodal* variety, we cannot see any principled reason why perceptual completion could not also occur *crossmodally* as well. That is, under those conditions in which the sensory cues associated with a multisensory object or event are made available to some, but crucially not all, of an observer's senses, it would seem plausible that one might expect to see some form of crossmodal perceptual completion, as the brain tries to figure out (or predict) what is really "out there." As modal and amodal completion, traditionally conceived, result in the perception of an object in one sensory modality (e.g. a visual object), crossmodal completion results in the perception of a multisensory object.

That said, those researchers who have documented cases of perceptual completion rarely, if ever, draw any explicit link between the phenomena they describe and crossmodal mental imagery. It is by no means clear why this is. It might be because people tend to think of perceptual completion as being necessarily of one of two kinds: Either it occurs in one and the same modality ("modal completion") or, if it does not, it lacks modal specificity ("amodal completion"). There is, however, no principled reason to restrict the notion of completion to these two kinds and exclude completion operating across sensory modalities. Another possible explanation for this exclusion is that people tend to put too much emphasis on the idea that mental imagery is voluntarily—or even internally—triggered. However, we would like to argue that this idea does not correspond to the phenomenon of mental imagery considered more widely, which can be externally induced and which can be said to exhibit various degrees of automaticity and voluntary control (see above discussion).

Interestingly, several other phenomena that one might like to consider as constituting additional examples of crossmodal mental imagery and/or crossmodal perceptual completion have been classified as examples of synaesthesia by some

Fig. 9.2 (**a**) One of the best-known examples of perceptual completion in the visual modality: the Kanizsa triangle (Kanizsa and Gerbino 1982); (**b**) a frequent case of perceptual completion where one perceives a single shape and an occluder, and not three distinct objects; (**c**) a representation of two possible perceptual interpretations of the same pattern of tactile stimulation. Note that the more "intuitive" interpretation depicted on the left is likely determined by the principles of perceptual completion and good form (reprinted with permission from Gallace and Spence (2011; Fig. 4))
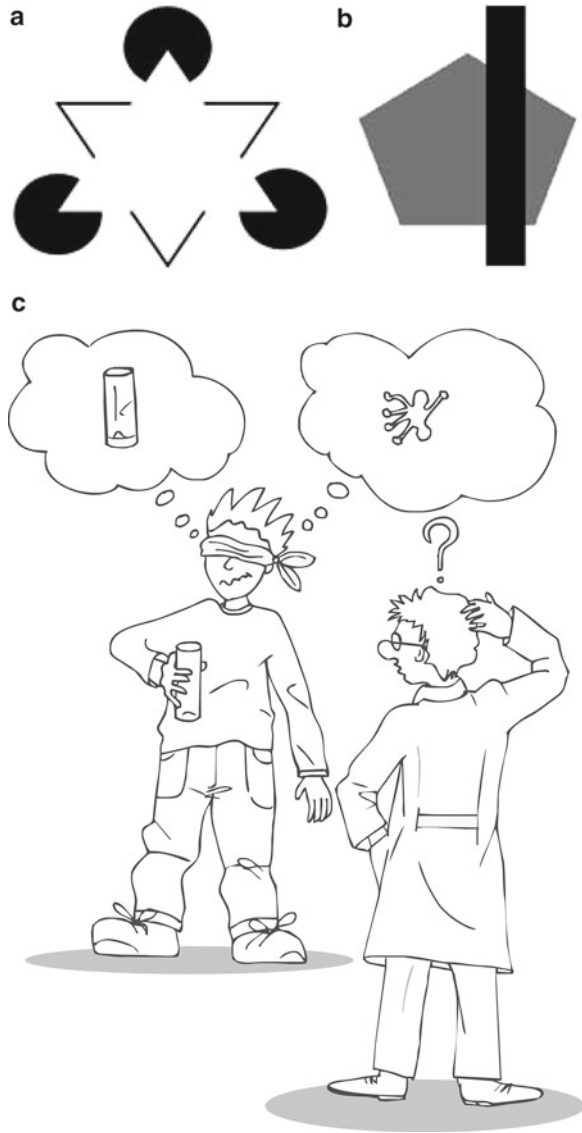
authors. For instance, in olfaction, certain smells are reported to give rise to taste sensations (as when the smell of vanilla or strawberry gives rise to the impression that a food or drink tastes sweet in Western participants, Spence 2008) and have recently been shown to activate insular (i.e. primary) taste areas in the brain (Veldhuizen et al. 2010; Verhagen and Engelen 2006). Stevenson and his colleagues have labelled this phenomenon "synaesthesia" or "universal and implicit synaesthesia" (e.g. see Stevenson 2009b; Stevenson and Boakes 2004; Stevenson et al. 1998; Stevenson and Tomiczek 2007; Verhagen and Engelen 2006). However, as the

argument outlined here has hopefully made clear, such findings are, in fact, equally compatible with an explanation (or description) in terms of crossmodal perceptual completion or crossmodal mental imagery.[4]

9.9 Crossmodal Mental Imagery in the Absence of Vision

A quick scan of the empirical literature reveals many examples of situations in which an individual is denied information that would normally be available concerning an object from one or more of their senses. The most frequently reported examples of crossmodal mental imagery in the normal population appear to come from those studies in which participants are denied *vision* of an object sensed by another modality (or modalities, be it touched, heard, smelled, and/or tasted). So, for example, when participants are blindfolded (or placed in darkness) and given an object to explore haptically, say, they will often spontaneously report using/generating visual imagery (e.g. Sathian and Zangaladze 2001; Zhang et al. 2004; see also Intons-Peterson 1992). Under such conditions, people often say that it is almost as if they can see the object that they happen to be palpating. Such subjective reports have now been backed up by neuroimaging evidence (e.g. Lacey et al. 2010; Lacey and Sathian 2012). For example, Zhang et al. have demonstrated that self-reported ratings of the vividness of visual mental imagery correlate with the amount of haptic shape-selective activity seen in the right lateral occipital complex.[5]

Similarly, increased neural activity in early visual brain areas has also been reported under those conditions in which a person is trying to identify a fragrance in the absence of the object that is normally associated with that odour (Qureshy et al. 2000; Royet et al. 1999). The situation in which we are presented with an odour that we know to be familiar but whose identity eludes us is known as the "tip-of-the-nose" phenomenon (Lawless and Engen 1977). People who find themselves in this situation often report trying to generate the visual image that is associated with the odour

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[4] We will not delve further into this difficult example here given the problem of knowing whether the influence of olfaction on taste should be treated as crossmodal or else merely as components of a unified flavour sense (Auvray and Spence 2008). Note also that experts have been reported to be able to exert some degree of *voluntary* control over whether or not this form of integration takes place (see Peynaud 1996; Smith 2007).

[5] As an aside here, it is worth noting that an alternative interpretation of the crossmodal brain activations of putatively visual areas under conditions of tactile/haptic stimulation in terms of crossmodal mental imagery has kept many a neuroimager awake at night over the years (e.g. see Hagen et al. 2002, p. 962; Lacey and Sathian 2012, p. 180, and Chap. 14 this volume; Ptito et al. 2005, p. 611). This suggests the reality of crossmodal imagery to many of the researchers in the field or, if not to the researchers themselves, then, at least to the reviewers of their papers. See Sathian et al. (2004) for intriguing evidence concerning how one might discriminate the crossmodal imagery account from other explanations using transcranial magnetic stimulation (TMS) and/or event-related potential (ERP) evidence.

in order to put a name to it in the absence of the appropriate visual cues. Wolpin and Weinstein (1983) have even found that the simultaneous presentation of a congruent olfactory stimulus can lead to reports of visual images that are more vivid than when an odour that was incongruent with the visual mental image was presented.

One important point to draw out from these studies is that it is often unclear whether the mental imagery elicited by the presentation of a stimulus in one modality (touch or olfaction, say) immediately gives rise to imagery in the modality that is not being stimulated (vision, say). Alternatively, visual imagery may be elicited in more of a top-down or *strategic* manner in order to help the participants identify the object/ stimulus that they have been exposed to (see also Djordjevic et al. 2004; Hubbard 2010; see Chap. 11). Notice here that the case will only count as crossmodal imagery if, as said earlier, the representation involved is not conceptual: That is, if perceivers who are presented with the odour explicitly look for hypothetical sources in their stored conceptual knowledge, and if this conceptual judgment is sufficient to explain the occurrence of the visual imagery (say, that they visually imagine a lemon because they suppose that this odour might be "of a lemon"), then the visual imagery has not been crossmodally induced, but is rather just an instance of mental imagery generated in a *top-down* manner. There are nonetheless good reasons to believe that not all strategic resorts to visual imagery are of this kind and that visual imagery can be mediated in a top-down fashion by strictly sensory representations, as when reaching for an object in the dark (see Kilintari et al. 2011, for recent neurological evidence in rhesus monkeys). In that case, a visual image is generated not to "perceptually complete" the movement: It strategically helps with action guidance in the absence of visual guidance and with the representation of the possible target (plausible when it comes to humans, as demonstrated by Sathian and Zangaladze 2001, and Darling et al. 2007). This kind of top-down processing can be explained by a feedforward model (e.g. Friston 2005, Friston and Stephan 2007; see Clark, forthcoming for a review) and does not require that an explicit hypothesis be formed.

Descriptions of the tip-of-the-nose phenomenon certainly often make it seem less a matter of crossmodal perceptual completion and more an example of the strategic (or voluntary) internal generation of a range of different visual images in order to try and help the individual concerned to identify the odour concerned. It is an open question as to whether all or just some of the instances of the phenomenon fall in what we have called mediate crossmodal mental imagery or whether they are just the effect of an inferential strategy.

So are we dealing with one function or two? It can, though, perhaps be argued that these two situations (haptic perception in the dark and sightless odour identification) are really more similar than they might at first seem. In the tip-of-the-nose situation, the olfactory inducer may not be perceptually rich enough to narrowly constrain the visual images that are generated in response to the presentation of the odour and achieve thereby a form of determinate modal completion. By contrast, it could be that the stimuli used in studies of sightless palpation may have provided haptic inputs that were sufficiently rich that they aided participants in more narrowly constraining the range of visual stimuli that could be consistent with (i.e. that would match) the haptic inputs. In both cases, it seems important to note that

mental images might only become conscious, or available for immediate report, over a certain threshold of vividness/resolution (see also Baars 1996).[6]

Another important point to draw out from the studies reported in this section is that crossmodal mental imagery effects appear to be somewhat *asymmetrical*. That is, while few of the participants in Zhang et al.'s (2004) study reported the spontaneous generation of haptic mental imagery during visual shape perception, the majority reported the frequent occurrence of visual mental imagery during haptic shape perception/recognition (see also Sathian et al. 1997). Similarly, it would not seem unreasonable to suggest that visual images are more often generated in response to the presentation of an olfactory cue, whereas the visual presentation of objects (e.g. when we happen to be watching a film at the cinema, say) rarely seems to lead to the *spontaneous* generation of olfactory imagery (except, perhaps, in the case of disgusting images; see also Lindauer 1969). Relevant here also are observations made by Intons-Peterson (1992): As mentioned already, she noted that when her participants generated an *auditory* image of a familiar event, they also reported generating a *visual* image as well. In fact, it turned out that visual images were generated in 95% of cases. By contrast, only 53% of people tasked with generating a visual mental image also reported producing an auditory image. Intons-Peterson (1992, p. 62) ended up concluding that "visual imagery has moderate primacy over auditory imagery".

Such differences (or asymmetries; should they prove reliable) may perhaps be related to the gross differences in the proportion of the cerebral cortex that happens to be devoted to the processing of information in each of the senses. According to Felleman and van Essen (1991), far more of the neocortex is given over to the processing of visual information (cf. 55%) than to the processing of information from any other modality (e.g. audition <12%; touch <4%; taste <1%; see also Gallace et al. 2012, on this point). Another intriguing hypothesis here is that the use of crossmodal mental imagery to help in multisensory object identification may just turn out to be less useful when the object in question is seen clearly—because of the accuracy and richness of visual information in object recognition (cf. Amedi et al. 2005). This would be consistent with the general idea of visual dominance but would here exhibit what we might call "visual monopolisation": That is, visual information is self-sufficient when it comes to providing perception of a complete object or object identification.

Some years ago, Klatzky and Lederman (1987) raised the possibility that the haptic recognition of objects might even *require* prior visual recognition (or at the

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[6] It is certainly true that visual object imagery seems to be more closely linked to haptic shape perception under those conditions in which the objects themselves are familiar to the participants under study (see Lacey et al. 2010). Indeed, in certain other cases (e.g. as when visualising the face associated with the voice that we happen to be listening to), the occurrence of crossmodal mental imagery (or crossmodally induced neural activation) seems to be more task-dependent than in others (see von Kriegstein et al. 2005; see also Royet et al. 1999). Once again, we believe that resolving the extent to which crossmodal mental imagery is externally versus internally generated, as well as clarifying the role of vividness, resolvability, and familiarity, will all likely constitute fruitful direction for future research.
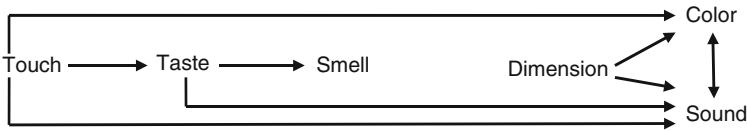
Fig. 9.3 Schematic representation showing the route by which sensory adjectives (synaesthetic metaphors) transfer their meaning from one sensory modality to another. The fact that we describe certain colours as "warm" would, for example, be consistent with the arrow going from touch to colour (figure reprinted with permission from Williams (1976, Fig. 1))

very least translation into a visual image), but their research eventually ruled out this possibility (see also Held et al. 2011, for a demonstration of excellent haptic identification in congenitally blind participants). A more interesting hypothesis to explore here would be if the difference between the visual images frequently generated in response to sightless haptic perception and the comparatively less vivid or frequent haptic images documented in cases of visual shape perception played a role in explaining the differences in people's aptitude when it comes to visual/haptic crossmodal shape matching.

As just highlighted, it turns out that many of the best-documented cases of crossmodal mental imagery come from those situations in which the inputs from one sense, typically vision, normally associated with a multisensory object or event, are not available. The presence of such nonvisual stimuli often appears to elicit visual imagery associated with the object or event that happens to be being felt (Lederman et al. 1990), heard (for instance, the facial imagery that can be elicited when listening to voices, von Kriegstein et al. 2005), smelled (Qureshy et al. 2000; Royet et al. 1999), or tasted (as is presumably the case in dine-in-the-dark restaurants; see Spence and Piqueras-Fiszman in press, for a review). Recent models have started to explore the ways in which mental imagery could help stimulus identification in an even more straightforward manner, by biasing perceptual experience itself through short-term memory traces (Pearson et al. 2008; Segal and Gordon 1969), thereby suggesting a bridge between the two apparently distinct functions of crossmodal imagery—that is, providing modal completion and strategically generating cues in a different modality.

The asymmetrical nature of crossmodal mental imagery (e.g. see Hubbard 2010; Zhang et al. 2004) is, then, most certainly a topic worthy of further consideration. It would be particularly interesting, for example, to determine whether there is any relationship between the asymmetries between sensory modalities observed in the case of crossmodal mental imagery and the asymmetrical transfer of sensory descriptors (i.e. adjectives) from one sensory modality to another that has been documented by Williams (1976) and others (Ullman 1945, 1957; see Fig. 9.3). Having addressed the question of whether crossmodal mental imagery can be considered as a kind of crossmodal perceptual completion, it is now time, finally, to assess the similarities and differences between crossmodal mental imagery and synaesthesia.

9.10 Distinguishing Between Crossmodal Mental Imagery and Synaesthesia

Once one starts talking in terms of people having conscious experiences in a given sensory modality in the absence of the corresponding sensory input, and once one starts thinking in terms of experiences that are induced by stimulation, or imagination, in another modality, one is unavoidably brought to the topic of synaesthesia (see also Chap. 10). The link between mental imagery and synaesthesia goes back a long way. Indeed, it is probably no coincidence that in the closing decades of the nineteenth century, when the very first systematic studies were being conducted, those individuals documented as exhibiting synaesthesia (e.g. chromoaesthesia, or coloured numbers, and/or mental number lines) were often described as exhibiting nothing more unusual than especially vivid mental imagery (e.g. Galton 1880b, c; Galton 1881; see also Barnett and Newell 2008; Hubbard 2010; Rader and Tellegen 1987; Riggs and Karwoski 1934). Similarly, early reports of musical imagery, that is, of individuals reporting vivid visual concurrents (or mental images) specifically in response to music (e.g. Karwoski et al. 1942; MacDougal 1898; Newton 1890), also tend to describe individual case studies that fall somewhere between what we would nowadays want to call crossmodal mental imagery and crossmodal sensory synaesthesia.[7]

Once again, though, before we can hope to assess the similarities and differences between crossmodal mental imagery and crossmodal sensory forms of synaesthesia, we need a working definition of the latter. According to one influential review, synaesthesia can be defined as "a conscious experience of systematically induced sensory attributes that are not experienced by most people under comparable conditions" (Grossenbacher and Lovelace 2001, p. 36). In terms of this definition (see also Bargary and Mitchell 2008; Ward and Mattingley 2006), (1) synaesthesia involves the elicitation of a *conscious concurrent* in the absence of the appropriate sensory input (in this regard, it is obviously indistinguishable from mental imagery); (2) the concurrent is *systematically* induced by a given inducer (again this seems similar to at least certain examples of crossmodal mental imagery—e.g. those examples that can be described in terms of crossmodal perceptual completion); and (3) the concurrent is *idiosyncratic* in the sense that few people systematically experience the same concurrent in response to a given inducer (see also Day 2005). In this regard, crossmodal perceptual completion-like mental imagery appears to differ from synaesthesia, although, of course, other examples of crossmodal mental imagery

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[7] Inclusion of the term "sensory" when discussing synaesthesia is necessary here to distinguish those forms of synaesthesia that are triggered by sensory inducers (and which are of interest here) from more "conceptual" forms of synaesthesia, where the synaesthetic concurrent is triggered by words (Simner 2007), personality traits (Riggs and Karwoski 1934; Ward 2004), and/or even swimming styles (e.g. Nikolić et al. 2011). Others use different terms to highlight this distinction—Day (2005), for example, distinguishes between "synaesthesia proper" and "cognitive" or "category synaesthesia" (see also Novich et al. 2011).

(e.g. those kinds that are more voluntarily induced or conditioned) are likely to be more or less idiosyncratic (see Leuba 1940).

However, in addition to the three defining characteristics, many other researchers typically add a fourth defining characteristic, namely, that the concurrent should be elicited *involuntarily* by the inducer (e.g. Bargary and Mitchell 2008). Finally, given the discussion outlined here, we would be tempted to add a fifth characteristic feature of synaesthesia, namely, that participants experience a lack of *conscious control* over the vividness of the concurrent (that happens to be automatically induced) and also lack any ability to transform it (thus contrasting with many cases of crossmodal mental imagery; see also Deroy and Spence 2011).

Thinking about the similarities and differences between crossmodal mental imagery and crossmodal sensory forms of synaesthesia, it can be seen that both involve the occurrence of vivid concurrents as a result of the presentation of specific physical inducers (or the imagination of those inducers). Both also involve conscious concurrents in the absence of the appropriate sensory inputs. However, where crossmodal sensory synaesthesia appears to differ from crossmodal mental imagery is that the crossmodal mapping in the former case is much more idiosyncratic within an individual and much rarer across the population as a whole than crossmodal mental imagery and may be induced more automatically and be under less conscious control.[8]

Given the evidence reviewed here, it can be argued that crossmodal mental imagery falls somewhere between irregular but voluntary mental imagery, as posited both by common sense and classical definitions, and crossmodal sensory synaesthesia: The former lacks the fixed mapping between the inducing sensory stimulus and the identity and/or vividness of any concurrent mental image, which is observed in cases of crossmodal mental imagery, whereas the latter, although it presents regular concurrents like crossmodal imagery that lies at another extreme in terms of this regularity (in that a given inducer will *always* give rise to exactly the same concurrent), is more involuntary and is highly idiosyncratic in terms of the crossmodal mapping between the inducer and the concurrent. Of course, one problem that arises once attention is drawn to the underlying similarities between these two phenomena is whether to treat crossmodal mental imagery and crossmodal sensory forms of synaesthesia as distinct psychological phenomena (see also Deroy and Spence 2011). Certainly, it can sometimes be very difficult to distinguish between them in practice (e.g. Rader and Tellegen 1987). Indeed, one might even consider whether they reflect the same underlying phenomenon, varying merely in degree (e.g. in the vividness of the associated concurrents; see Hubbard 2010; though see also Baars 1996).

We would like to argue here that differences between "mirror touch" synaesthesia—a phenomenon where people report experiencing tactile sensations in the location

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[8] Of course, the notion of idiosyncracy isn't especially well defined here. It is unclear, for instance, whether what is being talked about is idiosyncracy in terms of the nature (or subject matter) of the concurrent, the frequency of occurrence of the concurrent in the population, or both. Our view is that cases of mirror-touch synaesthesia (e.g. Banissy et al. 2009; Banissy and Ward 2007; Blakemore et al. 2005; see also Gates and Hupé 2011) seem to muddy the waters somewhat here.

(or, in certain individuals, in the specular, or mirror image, location) where they see someone else being touched—and the phenomenon of sound-induced touch we mentioned earlier (Kitagawa and Igarashi 2005) appear to fall uneasily at the borderline between crossmodal mental imagery and crossmodal sensory synaesthesia. Similarly, coloured hearing synaesthesia and the various crossmodal forms of musical imagery that have been reported, as well as cases like smelled sweetness (see Stevenson and Boakes 2004, for a review), are also difficult to firmly ascribe to a specific category.

However, given that a full discussion of these difficult cases falls beyond the scope of this review, we will simply state for now that we believe that the key difference between crossmodal sensory synaesthesia and crossmodal mental imagery is in terms of the regularity/idiosyncrasy of the inducer/concurrent relationship both within an individual and across the population as a whole Deroy and Spence (2011). One potentially important further difference here is that crossmodal mental imagery can be characterised in functional terms (e.g. Ahsen 1997), whereas the function of the synaesthetic experience remains rather more opaque (see Auvray and Deroy, in press, for a fuller discussion of these issues; though see also Stevenson and Case 2005).

9.11   Conclusions

In this review, crossmodal mental imagery has been defined as occurring whenever the physical (or imagined) presentation of a stimulus in one sensory modality results in the formation of a mental image in another modality. Given this definition, several phenomena crop up as providing possible exemplars (see Table 9.1).

At the same time, we have argued that one needs to distinguish rather carefully between crossmodal mental imagery and other putatively similar (and oft-confused) phenomena, such as crossmodal sensory synaesthesia and multisensory mental imagery. While many examples of crossmodal mental imagery appear to reflect nothing more than a kind of crossmodal perceptual completion, other examples appear to be less closely tied to a particular inducing stimulus and also to be under a somewhat greater degree of voluntary control.

Just like in cases of unimodal mental imagery, we believe that there are likely to be large individual differences in the vividness of crossmodal mental imagery (see also Rader and Tellegen 1987). Of course, as for the various mental phenomena with which it bears close comparison (e.g. crossmodal sensory synaesthesia and unimodal mental imagery), neuroimaging data will likely prove crucial in helping the "true believer" to convince the sceptic (should there be such) of the reality of the underlying phenomenon (e.g. Cohen Kadosh and Terhune 2012), given the likely widely varying incidence (or vividness) of the phenomenon between individuals.

In future research, it will also be interesting to assess the utility of the definition put forwards here in terms of clarifying the distinction between mental imagery, sensory forms of synaesthesia, and hallucination (e.g. MacDougal 1898; Sedman 1966; Segal 1971; Stevenson and Boakes 2004; Stevenson and Case 2005; Symons 1993),

Table 9.1 Overview of documented and candidate cases of crossmodal imagery

Image Inducer	Vision	Audition	Gustation/flavour	Olfaction	Touch
Vision	N.A.	Silent speech (see present discussion of Calvert et al. 1997)	Simmons et al. (2005)	Candidate: olfactory imagery induced by food-related pictures and pictures of disgusting objects	Auditory tickling (Kitagawa and Igarashi 2005)
Audition	Musical imagery (e.g. MacDougal 1898; Newton 1890)	N.A.	Candidate: Sounds of textured foods inducing flavour images		
Gustation/flavour	Candidate: Dining in the dark cases		N.A.		
Olfaction	Olfactory-induced visual imagery (e.g. Wolpin and Weinstein 1983)		Flavour images induced by smells (see Spence 2008; Stevenson et al. 1998)	N.A.	
Touch	Grasping in the dark (e.g. Kilintari et al. 2011); visual imagery in tactile perception (e.g. Lacey et al. 2010; Sathian and Zangaladze 2001)				N.A.

Notice that we remain neutral as to whether such cases will be found across all modalities in normal individuals and as to which cases will be found in sensory impaired individuals. Where/if vision is indeed dominant, one would expect that the sight of an object would not need crossmodal imagery/crossmodal completion.

especially in various special cases, be it those on drugs (e.g. Ellis 1902; Simpson and McKellar 1955; see also Brang and Ramachandran 2008) or those suffering from the long-term absence of some kind of sensory input (e.g. in the blind; see De Volder et al. 2001; Redlich and Bonvicini 1907; Steven and Blakemore 2004).

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Chapter 10
Is Synesthesia a Form of Mental Imagery?

Catherine Craver-Lemley and Adam Reeves

Abstract Synesthesia occurs when the activation of one sense modality elicits an experience in another modality. Synesthetic experiences are often referred to as *imagery*, and indeed both mental imagery and synesthesia occur in many sense modes and can represent forms of internally generated sensory experiences. However, they differ in prevalence, effects on perception, how voluntary they are, and probably in sites of brain activation; moreover, imagery and synesthesia are clearly differentiated by synesthetes themselves. We conclude that they are best considered as related but distinct mental processes.

Keywords Mental imagery • Synesthesia • Perky effect

10.1 Introduction

Synesthesia occurs when the stimulation of one sensory modality (e.g., hearing) reliably causes an involuntary and simultaneous perception in the same or in another modality (e.g., vision). For example, TH, one of our synesthetic participants, sees a tan circle that moves and stretches when he hears middle C being played on the piano, while for another of our participants, EC, viewing the color yellow elicits a very sweet taste that she likens to sugary cupcake frosting. There are many documented forms of synesthesia in part because it can involve any of the senses. Day (2005) documented 35 forms of synesthesia based upon surveys of 572

C. Craver-Lemley (✉)
Department of Psychology, Elizabethtown College, One Alpha Drive,
Elizabethtown, PA 17022-2298, USA
e-mail: lemleyce@etown.edu

A. Reeves
Department of Psychology, Northeastern University, Boston, MA, USA

Fig. 10.1 DR's grapheme colors. DR noted that the letter J actually appears with five different shades of *blue*. She has included two numeral 4s because the numeral 4 reportedly flickers back and forth between these two colors

synesthetes, but another account indicated there are as many as 152 forms (Ramachandran et al. 2004). Vernon (1937) defined synesthesia as a phenomenon in which "a stimulus presented in one sense mode seems to call up imagery of another mode as readily as that of its own" (p. 205); Cytowic and Wood (1982) also regarded synesthesia as cross-modal. However, synesthesia often involves the primary evoker, called the *inducer*, and the extra synesthetic experience, known as the *concurrent*, in the same sense (Grossenbacher and Lovelace 2001). For example, an individual with grapheme-color synesthesia sees a specific color when viewing a specific letter or digit, regardless of the actual ink color. DR, a grapheme-color synesthete and one of our research participants, perceives the letter *C* to be yellow, even when it is printed in another color such as black or pink (see Fig. 10.1).

Whether the concurrent and inducer are in the same sense or not, synesthesia has often been taken to be a special case or unique form of mental imagery. For example, McKellar (1957) refers to synesthesia as a form of imagination experience (p. 51); Roeckelein (2004) reported synesthesia to be "closely related to sensory imagery" (p. 69; see also McKellar 1957); and more recently Mattingley and Rich (2004) described grapheme-color synesthetes' colors as being "seen as a 'mist' or as a colored overlay in space, or as a vivid form of mental imagery 'in the mind's eye'" (p. 851). The view traces back to Galton (1907), who noted similarities between synesthetes and eidetic imagers. (Eidetic imagers report detailed and vivid percept-like images, much more vivid and much longer lasting than typical memory images: Haber and Haber 1964; see also Brang and Ramachandran 2010; Roeckelein 2004.) Indeed, an intriguing finding is that 10% of synesthetes are also eidetic imagers, a much higher proportion of eideticers than is found in the general population, perhaps suggesting a link between synesthesia and this form of imagery.

In this chapter, we ask, "Is synesthesia a form of mental imagery?" Whereas the above-mentioned psychologists appear to have classified synesthesia as mental imagery, the synesthetes we have interviewed all tell us that their mental images are quite distinct from their synesthetic percepts. First, we will provide a brief historical background highlighting recent parallels between psychological investigations of synesthesia and of mental imagery. Then we will discuss (in no particular order) six aspects of both mental imagery and synesthesia which have been investigated, noting how they may or may not differ. The aspects are prevalence, inducers, experienced location, relation to perception, phenomenology (vividness and controllability), and neural correlates.

10.2 Brief History

Accounts of synesthesia have appeared throughout the literature for centuries (see Dann 1998 for review). Galton, who studied mental imagery, also described many forms of synesthesia (Galton 1907). The early psychological literature was mainly comprised of case studies such as a report by Coriat (1913) describing a former psychoanalytical patient for whom sounds evoked various shades of blue, cardinal numbers produced a visual-spatial arrangement, the seasons elicited shapes, and colors triggered taste. Langfeld (1914) discussed the synesthesia of a musician-composer for whom tones caused the appearance of colors. Additional studies describing synesthesia through subjective reports continued until around 1930 when the behaviorist movement became dominant, and the study of cognitive processes was temporarily derailed. According to the radical behaviorists, the earlier emphasis on mental processes had prevented the field of psychology from developing into a recognized science; psychologists should limit their studies to observable stimuli and behaviors. Mental imagery and synesthesia exemplified private events that could not be directly observed. It was not until the 1960s that psychologists in general began once again to study cognitive processes. One of the valuable contributions of the behaviorist paradigm was the emphasis on experimental controls. Researchers were challenged to conduct scientific studies that would establish that hidden cognitive processes were genuine. Thus, research in 1960s and 1970s was directed toward empirically demonstrating the existence of mental imagery (Shepard and Metzler 1971; Kosslyn et al. 1978; Segal 1971).

Research in synesthesia reemerged later and, similar to research in mental imagery, initial work was dedicated to demonstrating that synesthesia is indeed a genuine phenomenon, that is, has potential for scientific explanation and is experimentally reproducible. For example, some early accounts suggested that synesthesia may depend on learned associations (Calkins 1895; Galton 1880, 1907). How might such an association occur? Leuba (1940) conducted a study using Pavlovian techniques to demonstrate that a mental image could be considered a "conditioned sensation" (p. 351). For instance, during one of his demonstrations, he paired rubbing

a participant's arm with the presentation of creosote (his participant was hypnotized during the pairing). Later, Leuba's participant would perceive an olfactory image of creosote whenever his arm was rubbed although he had no memory of making this cross-modal association. However, as such learned associations are rarely reported by synesthetes, authors have searched for additional explanations (e.g., Cytowic 2002; also see Brang et al. 2011; Hancock 2006; Simner et al. 2005; Witthoft and Winawer 2006, did draw attention to a single case in which synesthetic concurrents were based on a colored alphabet seen in childhood, but these authors concluded that synesthesia is not simply a memory association, p. 183.).[1]

Since the 1980s, Cytowic has helped to popularize synesthesia in both the public and scientific arenas. Particularly captivating was his account of a synesthete for whom specific flavors would trigger unique tactile sensations mainly upon his shoulders or hands (Cytowic 1993; Cytowic and Wood 1982). Cytowic went beyond simply presenting the public with a fascinating case study; he conducted an experiment that tested for consistency in order to test the genuineness of synesthesia. Likewise, Langfeld (1914) had followed up on earlier testing that he had conducted with a music-color synesthete by playing notes on the piano and recording the synesthetic colors that each note produced. Although the testing sessions occurred more than seven years apart, Langfeld found "… almost perfect agreement between the two investigations. The subject assured me that she had never given any thought to the investigation in the interim" (p. 114). Baron-Cohen et al. (1987) developed a test of the consistency of synesthetes' concurrents over time that is often used by researchers to screen potential research participants. Eventually Cytowic and other researchers, including Baron-Cohen, Ramachandran, and Hubbard, established synesthesia as a worthwhile subject of investigation in the field, and synesthesia has become a popular topic of scientific study.

10.3 Prevalence

Mental imagery is much more prevalent than synesthesia; the vast majority of individuals report experiencing some form of mental imagery (Richardson 1969), both in dreaming and in the awake state. In contrast, synesthesia is rare; a large-scale

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[1] Witthoft and Winawer (2006) provided the first documented account of a synesthete whose concurrents stemmed from a childhood alphabet (a magnet set). Readers may care to know that one of the authors, AR, identified another case of grapheme-color synesthesia which also demonstrates a childhood foundation for concurrents. His sister, Angela Reeves, learned her letters in 1948 when she was 5 years old from a colored drawing of the alphabet made by her primary school teacher; the letters remained on the wall of the school into the 1960s when Angela was able to check them again. While there is evidence that experience can *influence* the development of concurrents (e.g., Witthoft and Winawer, 2006), the current literature does not support an account that is based solely upon a learned association. Grapheme-color synesthesia is a very common form of synesthesia; Day's (2005) survey of 572 synesthetes revealed that 69% experienced grapheme-color synesthesia, and clearly those who can trace their concurrents to childhood sources are extremely rare.

study reported 1 in 1,150 adult females and 1 in 7,150 adult males experience synesthesia (Rich et al. 2005). Still, it may be that synesthesia is more common than estimated, as some synesthetes report that their synesthesia does not interfere with their daily life so it may not be mentioned (i.e., it is not a problem, so why bring it up?). Also some synesthetes do not realize that their perceptual experiences are unique. For example, EC did not learn that she was a synesthete until graduate school when she happened to comment "Isn't it annoying how mustard doesn't taste like its color?" in the company of someone who knew about synesthesia (recall EC gets a sweet taste when viewing yellow). Others may intentionally elect to keep their synesthesia to themselves to avoid being teased or even punished. DR recalls being extremely agitated during kindergarten when a work booklet showed *C* colored pink, instead of yellow (DR's synesthetic color for this letter). Not understanding that this incongruence between her perception and physical reality was not shared by her classmates, she believed an error had been made. When she pointed out the *mistake* to her teacher she was admonished in front of the class. After this experience, DR learned to keep her synesthetic color experiences private. We can speculate that because many cases may go unreported, synesthesia may be more widespread than estimated; nonetheless it is unlikely to be anything like as prevalent as mental imagery.

10.3.1   Classification of Imagery and Synesthesia

Deciding whether synesthetic experiences are similar to mental images requires some attempt to define the nature and occasions of mental images themselves. Beyond the obvious classification of mental images by modality, psychologists have also classified mental images by the conditions that evoke them. For example, cross-modal imagery, imagination imagery, after imagery, and dream imagery (Richardson 1969) can be defined by the inducing stimulus; thus, *cross-modal* when an unexpected stimulus from one sense mode calls up an image in another mode (the scent of magnolia summons up an image of a relative standing in his yard) (see Spence and Deroy, this volume); *imagination* when creative thought can generate new combinations of ideas which evoke new images; *afterimage*, as when a departing stimulus leaves behind a trace, or aftereffect; and *hypnogogic* imagery, that is, dreamlike images in some people just before falling asleep. (Such a list leaves open the type of imaging experience which follows from the eliciting stimulus, e.g., visual images may be detailed or be skeletal: Fletcher et al. 1995; Kosslyn 1980.)

Richardson (1969) provided a formal definition of mental imagery including four criteria that encompass this wide range:

> *Mental imagery refers to (1) all those quasi-sensory or quasi-perceptual experiences of which (2) we are self-consciously aware, and which (3) exist for us in the absence of those stimulus conditions that are known to produce their genuine sensory or perceptual counterparts, and which (4) may be expected to have different consequences from their sensory or perceptual counterparts.* (pp. 2–3).

It may be argued that synesthesia meets the criteria designated in this definition. Synesthesia represents a quasi-sensory or quasi-perceptual experience which can occur within or between any of the sensory modalities. Synesthetes are aware of their synesthetic images, by definition: They can report on what they have heard, tasted, smelled, felt, or seen. Synesthesia occurs in the absence of *related* external sensory stimulation—for example, perception of a sound may generate a taste experience, and this taste experience does not involve any direct taste stimulation. Finally, synesthetes are aware that the concurrent is not *real*, so, like mental images, concurrents typically do not directly guide behavior; one does not try to erase a synesthetic color from a printed letter. Richardson's criteria are broad enough not to exclude synesthesia; distinguishing them must be on other grounds.

10.4   Imaginary Inducers

Interestingly, synesthetes have indicated that in addition to an external trigger, they can use mental imagery to induce their synesthetic percepts. In his early report, Langfeld (1914) noted that the music-color synesthete "… in fact could see the color at the mention of the musical note." (p. 113). Similarly, sound-color synesthetes we have tested are able to imagine tones from different instruments and detail how the visual concurrent induced by each instrument differs. Smilek et al. (2001) noted that thinking of a letter was sufficient to evoke the concurrent in grapheme-color synesthesia. Barnett and Newell (2008) found that 36 of 38 synesthetes they sampled reported that imagining an inducer would evoke a synesthetic percept. In our lab, EC reports that imagining some colors evokes a *ghost* of a taste, while for other colors it triggers tastes that are as intense as those experienced with a perceptual trigger.

Spiller and Jansari (2008) tested grapheme-color synesthetes to determine whether or not a visual mental image could trigger a synesthetic percept. Six grapheme-color synesthetes were each matched with a small group of controls. During phase 1, participants were asked to form an image of a grapheme inside a black outline circle presented on a white screen. Participants pressed a key to indicate when they had formed a strong image, and then the circle was divided into thirds with each section comprising either solid or dashed lines. During phase 2, participants reported which section of the circle contained most of their image, and response time and accuracy were measured. Importantly, also during this phase, the background of the screen either remained white or changed to a color that was either congruent or incongruent with the synesthetic color triggered by externally presented graphemes. The authors predicted that akin to findings with externally presented graphemes (e.g., Smilek et al. 2001), there would be a *congruency effect* for imagined graphemes among the synesthetes. A congruency effect would be revealed by longer response times when the grapheme color matched the background. However, only two of the synesthetes showed a congruency effect. Although Spiller and Jansari (2008) demonstrated that visual mental images can evoke synesthesia, their lack of a group effect highlights the
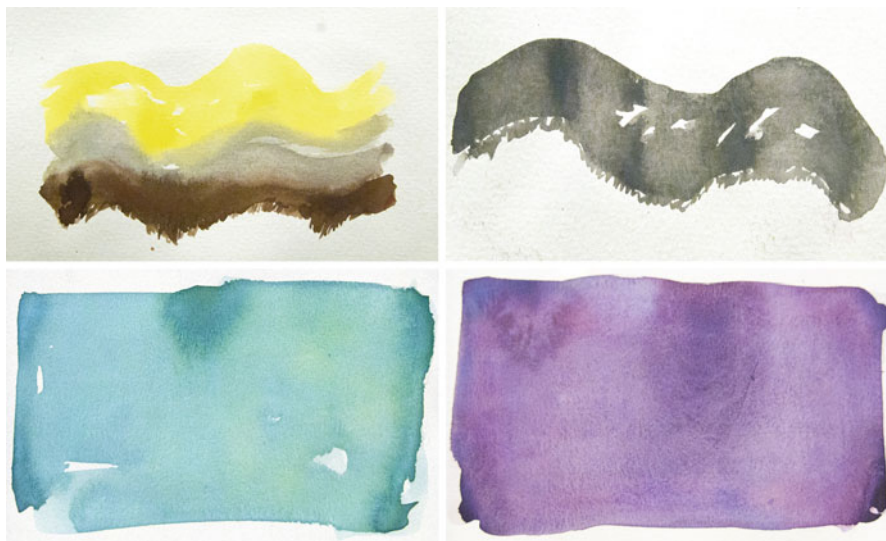
Fig. 10.2   TH's (*top*) and DR's (*bottom*) visual concurrents generated by the voices of artist Laura Bach (*left*) and Craver-Lemley's (*right*) voices. Both DR and TH report that their concurrents for voices vary according to timbre. These images were painted by Laura Bach under the direction of the synesthetes

issue of individual differences among synesthetes sharing the same form of synesthesia. For an example, compare the differences in DR's and TH's visual concurrents elicited by the same voices in Fig. 10.2.

10.5   Location

There are similarities regarding the location in which synesthetic percepts and mental images exist; in both cases images may be either internalized or externalized in space. For instance, researchers investigating synesthesia noted differences in where synesthetes reported their synesthetic percepts to appear. Based upon such observations, Dixon et al. (2004) termed synesthetes who see their colors externally in space as *projectors*, while those reporting that their colors occur internally, that is, in the *mind's eye* or *in my head* are said to be *associators*. There is evidence suggesting that the projectors and associators' distinction may reflect the activation of different neural mechanisms (e.g., van Leeuwen et al. 2011; Rouw and Scholte 2010).

When experiencing grapheme-color synesthesia, DR's synesthetic colors appear in external space, as a colored transparency overlaying the grapheme. Many other grapheme-color synesthetes also report their colors as external transparencies, but there are also accounts in which the colors are projected but adhere to the forms of the graphemes or they may appear internalized. In addition to grapheme-color synesthesia,

Fig. 10.3 Laura Bach and Catherine Craver-Lemley's written first names and person-colors (CL *top*; LB *below*) as they appear to DR. DR believes the halos surrounding the names may come from the letter *a*. For most grapheme-color synesthetes, a word will take on the color of an anchor letter. DR provided the colored words images; Bach painted the person-color concurrents according to DR's specifications. Note that the written names elicit concurrent colors that are different from those evoked when DR views the individuals

DR also perceives synesthetic colors when looking at people (Craver-Lemley et al. 2012). Unlike her grapheme-evoked colors, she reports that the synesthetic colors that she sees when she views people are visible either in her head or in front of her eyes and forehead, but not as a transparent overlay. Figure 10.3 provides representations of two forms of DR's synesthesia: synesthetic color images elicited by written words and those triggered when she views people. Besides these intramodal forms of synesthesia (graphemes or people triggered colors), DR also experiences cross-modal synesthesia in that music, voices, and some environmental sounds cause her to perceive colored shapes. These shapes are external, typically floating before her (as illustrated in Fig. 10.2) rather than adhering to seen objects (as shown in Fig. 10.1). DR also sees external colored images in response to olfactory stimuli; for instance, the scent of lily-of-the-valley triggers a purple shape that is externalized in space.

Like synesthetes, participants in mental imagery studies have reported their visual mental images to appear either internally *in my head* or to be projected externally *in front of me*. It has been suggested in the synesthesia literature that such individual differences involving the spatial location of the concurrent may influence experimental outcomes (e.g., Smilek et al. 2001; Ward et al. 2006). However, this does not appear to be the case with visual imagery. For example, comparisons of more than 150 of our research participants revealed that although there were differences regarding the location of the visual image (internalized or externalized in space) this difference did not influence the robustness of the Perky effect (imagery-induced interference for a perceptual task, see below).

10.6   Relation of Imagery and Synesthesia to Perception

Another parallel between imagery and synesthesia involves the relationship between each and perception. The question of what distinguishes a mental image from a percept was raised by Aristotle and by David Hume. Hume argued that everyday experience could not distinguish imagery from reality except on the basis of vividness, as an imagined face could be as detailed and (presumably for him) as external as a real one. Since there were no innate ideas in his Empiricist philosophy, and thus no way of distinguishing the real from the imaginary a priori, vividness must remain a key distinction even in the adult. A famous example of failure to distinguish visual images from percepts was Shereshevskii, a professional mnemonist, research subject, and synesthete. Luria, who tested Shereshevskii extensively, observed, "The boy was a dreamer whose fantasies were embodied in images that were all too vivid, constituting in themselves another world … He thus tended to lose sight of the distinction between what formed part of reality and what he himself could 'see.'…. How, after all, was S. to adjust to rapidly shifting impressions when the images that emerged from these were so vivid they could easily become reality for him?" (Luria 1968, pp. 151–152). The picture evoked by Luria seems compelling, yet possibly the most vivid imager in our lab has been an adult, LM, who reported being able to run internal movies at will. She even experienced images vividly enough to interfere with reading so, for example, upon reading a description of a horse and carriage, she had to move her image of the carriage sideways to make the text visible underneath the wheels. Nevertheless, she never reported confusing her images with reality in daily life. Shereshevskii and LM are extremes; but what of normal individuals?

Like others before her, Perky (1910) attempted to explore the qualitative differences between images and percepts. In what has become a classic experiment, Perky asked her participants to fixate at a mark on a window and to hold this fixation while imagining common objects (e.g., a book, a leaf). While they were imaging, dim pictures of the objects, which fluctuated in intensity and oscillated slightly, were presented at fixation from behind the window and slowly intensified until above threshold. Surprisingly, participants were unaware of the picture and yet their mental images often resembled the pictures, and they also described images in which parts of the stimulus had been merged with the image (Perky 1910, p. 432). Perky claimed that her participants' images were indistinguishable from the external stimuli because the participants did not report a perceptual experience and responded with *surprise* and *at times indignation* when asked if they had *imagined all these things* (p. 431). Perky observed "… under suitable experimental conditions, a distinctly supraliminal visual perception may be mistaken for and incorporated into an image of imagination, without the least suspicion on the observer's part that any external stimulus is present to the eye" (p. 450), and she concluded that "… the materials of imagination are closely akin to those of perception" (p. 451).

More recently there have been reports that imagery can be mistaken for percepts (Craver-Lemley et al. 1999; Finke et al. 1988; Intraub and Hoffman 1992). For example, following methods that have yielded illusory conjunctions, incorrect

combinations between features of objects under conditions of overloaded attention (Treisman and Schmidt 1982), Craver-Lemley et al. (1999) found that features of mental images and percepts could be incorrectly combined. Their participants, like Perky's (1910), incorporated imagery with percepts. However, in this case, participants reported a purely perceptual experience.

Although Perky (1910) concluded that the effect she discovered was a confusion between imagery and perception, Segal and colleagues provided evidence that her findings reflected a decline in sensitivity for a stimulus that is presented during concurrent imagery (e.g., Segal and Fusella 1969; Segal and Glicksman 1967; Segal and Nathan 1964). Confusion, or incorporation, does occur, but only rarely, whereas sensitivity is consistently lowered by imagery. Such imagery-induced interference for a perceptual task became known as the *Perky effect*. The Perky effect is not limited to the visual mode: Segal (1971) found that it occurs in other modalities as well, for example, imagining a bicycle bell lowers sensitivity to sound (see also Okada and Matsuoka 1992). The effect involves a true reduction in sensitivity (d'), not just an inefficient criterion, and it is modality specific, for example, auditory images interfere with hearing but not with seeing and vice versa (Segal and Fusella 1969).

In vision, Craver-Lemley and colleagues showed that visual images interfered with a Vernier acuity task (Craver-Lemley et al. 1997; Craver-Lemley and Reeves 1987; 1992; Reeves 1981) and a visual detection task (Craver-Lemley and Arterberry 2001; Craver-Lemley et al. 2009).

In the Vernier acuity task, participants were presented with two vertical lines, one above the other. The lower line was offset slightly to the left or to the right of the other line. Participants reported the direction of this offset. This acuity task was performed with and without concurrent visual imagery. Any image that overlapped with the target resulted in a robust Perky effect, regardless of whether or not it shared features with the target. Figure 10.4 shows a reduction in accuracy for real and imagined lines (Perky effect). This reduction in accuracy illustrates a localized interference effect, since merely having real or imagined lines present but several degrees of visual angle distant from the target does not lower accuracy (Reeves and Craver-Lemley 2012). Craver-Lemley and Reeves (1992) demonstrated that the Perky effect could not be accounted for by attentional distraction, optical changes (e.g., accommodation), poor fixation, or demand characteristics. They concluded that the Perky effect occurs because of a local, pattern-independent reduction in visual sensitivity produced in the brain by mental imagery. The Perky effect is pertinent to the imagery–perception issue as it assesses how imagery can influence an ongoing perceptual task.

The Perky effect has also been used to examine the involvement of top-down processes in synesthesia. For example, Butcher et al. (2002) reported that mentally imagining graphemes interfered with grapheme-color synesthetes' abilities to detect a grapheme. Moreover, the synesthetes' Perky effect was greater than that of the controls. Using a visual search task, Smilek et al. (2001) reported that a grapheme-color synesthete had difficulty identifying and localizing digits presented against backgrounds that were congruent with her synesthetic colors. For instance, the individual identified a black numeral 2, which evoked a synesthetic red, with less accu-

Interference by black, matched, or imaged lines
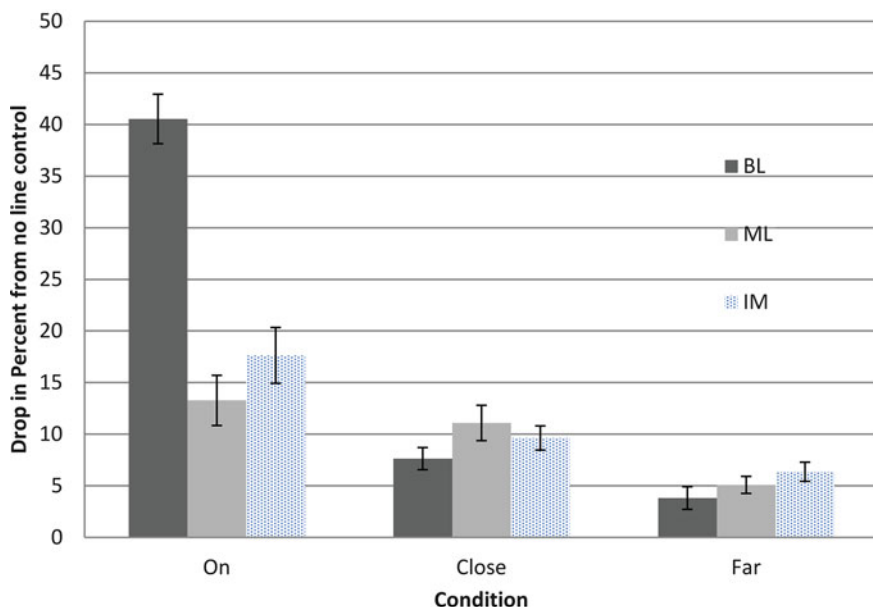
Fig. 10.4   Vernier acuity was measured under conditions in which physical *black lines* (BL), *imagined lines* (IM), or physical lines constructed by participants to *match* their *imagined lines* (ML) were presented or imagined concurrently with the target (Reeves and Craver-Lemley 2012). All lines reduced accuracy when they overlapped with the target (*on* condition), but this effect did not occur several degrees of visual angle from the target (*far* condition). The reduction in accuracy for IM reveals a Perky effect. Error bars show one standard error

racy when it was presented against a red background than when it was presented against a noncongruent, yellow background. We can conclude that, under certain circumstances, both mental imagery and synesthesia can interfere with perception, although too little research has been conducted with synesthetes to know if the spatial and temporal parameters of the interference are similar (Craver-Lemley and Reeves 1987).

Although there are situations in which people may confuse their images with percepts, and vice versa, this is typically not the case. Synesthetes know that an inducer is responsible for their synesthetic experience. Individuals engaged in mental imagery are intentionally evoking images and generally do not mistake them for reality, even if they are reportedly vivid (as with LM). Individuals that do so are classified as hallucinators and treated differently by society and by psychiatry. (However, hallucinations may be akin to images, the primary difference being in belief. A hallucinated voice may not seem different from an imaged one, in terms of vocal quality, pitch, expressiveness, and so forth, but it may appear as real, as compelling, and thus, as believable (Barber 1971)).

Many researchers have investigated the perceptual nature of synesthesia (e.g., Craver-Lemley and Mastrangelo 2009; Kim et al. 2006; Ramachandran and
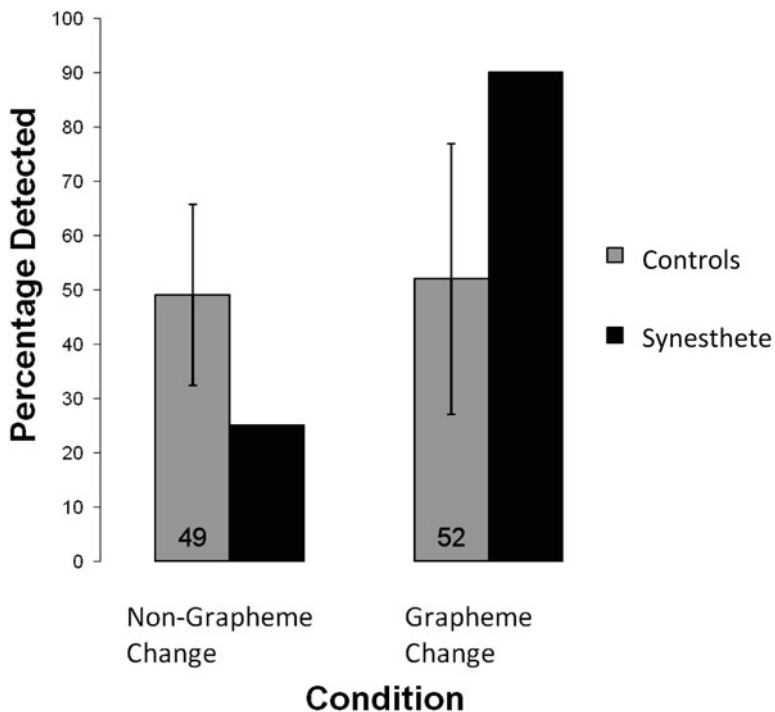
Fig. 10.5 A grapheme-color synesthete's accuracy on a change blindness task in comparison to 12 controls (Johnson and Craver-Lemley 2008). The synesthete demonstrated better performance at detecting grapheme-related changes than non-grapheme changes and was more accurate than controls at detecting grapheme changes. Error bars represent one standard deviation

Hubbard 2001a; Smilek et al. 2001); for example, researchers have found that synesthetic colors can have effects that are similar to real colors (e.g., Kim and Blake 2005; Palmeri et al. 2002; Ramachandran and Hubbard 2001b). For instance, Kim and Blake (2005) found that the watercolor illusion (Pinna et al. 2001) could be elicited by synesthetic colors. In other studies, synesthetes have completed visual search tasks in which the target elicited a different synesthetic color than the distracters (e.g., Laeng et al. 2004; Palmeri et al. 2002; Sagiv et al. 2006). In such cases the synesthetic target aided the search by allowing for more rapid recognition of the target. Also, as noted above Smilek et al. (2001) showed that when the target and distracter elicited similar colors, the search became less efficient (also see Blake et al. 2005). Ramachandran and Hubbard (2001b) presented grapheme-color synesthetes and controls with embedded shapes composed of graphemes surrounded by other graphemes. They demonstrated that synesthetes were better than controls at identifying the embedded shapes because of the grouping cue evoked by the synesthetic color. Johnson and Craver-Lemley (2008) discovered that a grapheme-color synesthete was both faster and more accurate than controls at detecting alphanumeric changes in a change blindness task. The synesthete performed more like controls when the changes were not grapheme changes which did not induce her synesthetic colors (Fig. 10.5).

Evidence that synesthetic colors can produce effects that are similar to real colors and thus enhance performance on perceptual tasks suggests another similarity between synesthesia and mental imagery in that there are circumstances under which mental images have been shown to weakly facilitate perception (Farah 1989; Farah and Smith 1983; Ishai and Sagi 1995, 1997). In Farah's studies of visual imagery, the primary effect of the image was to alter the criterion, rather than change sensitivity. However, Ishai and Sagi (1995), imaging a nearby Gabor patch slightly improved sensitivity to the visual target, also a Gabor. This result is opposed to the much greater pattern of interference (the Perky effect) found with line targets by Craver-Lemley and colleagues and with pictures by Segal and Fusella (1969); the discrepancy still needs explanation. All we can conclude with certainty is that visual perception may be influenced by imagery. The same applies with synesthesia; synesthetes may find that their synesthetic experience interferes with or facilitates performance during perceptual tasks. Clearly both mental imagery and synesthesia can interact with perception, but may do so in rather different ways, imagery predominantly interfering and synesthesia sometimes interfering and sometimes facilitating.

10.7   Phenomenology: Vividness and Controllability

Discussions of what it is like to have mental imagery have included the dimensions of vividness, how strong and controllable the image is, and the degree to which the content, location, and presence of the image are voluntary (Richardson 1969). A key feature of synesthesia is the vividness of the experience, and one of the diagnostic criteria for synesthesia is that it must be an involuntary and automatic experience (Cytowic 2002).

10.7.1   Vividness

Vivid mental imagery occurs in some experts—auditory in musicians; visual in painters, sculptors, and architects; flavor in cooks; smell in perfumers; touch in masseurs; and kinesthetic imagery in athletes, as is widely known and has been indicated to one of us (AR) in unstructured interviews. However, mental imagery may lack both consistency and vividness for many. From the earliest mental imagery studies (e.g., Fechner 1860), researchers have observed individual differences in imagery ability, especially in the visual domain. For example, in the 1880s, Galton asked people to recall their breakfast table and to describe this particular imagery experience. Reports of imagery ranged in vividness from as clear as the actual breakfast table to having no imagery at all (Galton 1907). Although it is obvious that individuals do show variation in the vividness of their imagery, we found in 79 individuals that the Vividness of Visual Imagery Questionnaire scores (VVIQ; Marks 1973), obtained before the experiment was run, did not correlate with the

strength of the Perky effect (Craver-Lemley 1988). Moreover, individuals reporting stronger imagery during testing had a similar Perky effect (19.3%) to those reporting weaker imagery (19.0%). In contrast, vividness does appear to predict latency for image formation (Paivio 1968). Smaller mental images (occupying less than 10° of visual angle) are faster to generate when vivid than when weak, but this pattern is reversed when the images are greater than 10° (D'Angiulli and Reeves 2007), perhaps because large, detailed, images take more time to complete (Kosslyn 1980). We note that ignoring image size could well cancel out this relationship.

Synesthetes often report strong or vivid imagery, and there has been a suggestion that visual-spatial synesthesia (such synesthetes experience a spatial arrangement of numerals and the months) might arise from childhood imagery strategies, indicating a link between strong imagery ability and synesthesia (Price 2009). Barnett and Newell (2008) administered the VVIQ to 38 synesthetes with different forms of synesthesia and to matched controls. The synesthetes' ratings revealed that their mental images were significantly more vivid than those of the controls. Price (2009) administered the Subjective Use of Imagery Scale (SUIS; Reisberg et al. 2003) and the Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova et al. 2006) to visual-spatial synesthetes and controls. Again, the synesthetes scored higher than the controls on visual imagery. Finally, Spiller and Jansari (2008) found that synesthetes were significantly faster to imagine graphemes than were controls, also suggesting that synesthetes possess stronger imagery.

Curiously, some synesthetes have reported that their mental images of concurrents can be stronger than the original concurrent (e.g., Ramachandran et al. 2004). Recently we asked two sound-color synesthetes, TH and DR, to describe their visual concurrents while a note was played on a synthesizer. An artist (Laura Bach) painted the concurrent as it was described by each of the synesthetes (TH and DR were individually tested). The note was played again and the synesthete was shown Bach's painting. At this time, Bach made adjustments according to the synesthete's specifications until the synesthete was satisfied that the painting was a realistic representation. Later the synesthetes were asked to recall a mental image of the original concurrent and to describe it for the artist until the artist had painted an accurate depiction. Finally, the synesthetes were asked to imagine the tone and to describe the concurrent it induced as it was painted. Three different tones were used to elicit the concurrents, producing nine paintings for each synesthete. DR's results are shown in Fig. 10.6. DR described her mental images of her concurrents as being more vivid than the original concurrents, as inferred from Bach's depictions. Although DR's auditory mental image of the tone did indeed elicit visual concurrents, this experience was reportedly less vivid and included variations from the original. On the other hand, TH reported his visual concurrents to be *pretty much identical* in all three conditions (not shown here). It is worth mentioning that TH's color vision is limited; he does not report perceiving red, orange, or green, and this inability extends to his visual concurrents (all are described as brown, gray, yellow, or white). TH's experience is in contrast to a color-blind synesthete reported by Ramachandran (e.g., Ramachandran 2004) whose visual concurrents provided him with color experiences he could not experience without synesthesia. TH's synesthetic

Fig. 10.6 DR's visual concurrents for three musical notes varying in pitch (*left column*), mental images of these concurrents (*middle*), and concurrents generated by auditory mental images of the same musical notes (*right*). Each row shows DR's experiences generated by the same note. Pencil notations at the top identified the conditions for the artist, Laura Bach, who painted the concurrents under DR's instruction

percepts are in keeping with his non-synesthetic color perception, again illustrating the difficulty of drawing general conclusions from the idiosyncrasies of synesthetic reports.

10.7.2 Controllability

Mental imagery can occur spontaneously (automatically seeing someone in the mind's eye when hearing her voice over the phone) or it can be voluntary (intentionally visualizing a friend). So an important distinction between mental imagery and synesthesia is that mental imagery may be controlled whereas synesthetic imagery is automatic. Since imagery can be voluntary, people can use it to solve problems (e.g., in geometry) or help them to recall information (e.g., by association). The ability to control and manipulate images may be measured in self-report tests such as Gordon's Test of Visual Imagery Control (Richardson 1969). Although some individuals report finding it hard or impossible to control their mental imagery, others find it easy to do so, and they report being able to control even small details

of their imagined depictions. In strong contrast, no synesthete has reported having detailed control over their concurrents, although interestingly, DR said that her concurrent for one of the notes extended as far as she could see and that she could *zoom in* on it in order to provide more details for the artist. TH also remarked that he had *focused on* one feature of a concurrent in order to provide better contrast between two concurrents of different people (see Fig. 10.2). These comments are reminiscent of how individuals reportedly scan and zoom in on their visual images (e.g., Kosslyn 1973; 1975; also see Kosslyn et al. 2006), even though they do not imply that the synesthete can alter details, such as the color.

We can summarize by saying that, unlike visual imagery, which is largely voluntary if not always under precise control, synesthesia is typically involuntary; it is closer to perception than imagery, in that you get what you see, hear, taste, smell, feel, and so forth, without the possibility of modification. The *zooming* reported by DR does show a degree of control, in that an object can be brought closer to the face, but it does not involve a change in any of the details. Although synesthetes may trigger their synesthesia by intentionally imagining an inducing stimulus, they report being unable to prevent a concurrent when presented with a perceptual inducer.

10.8   Neural Correlates

A recent approach to comparing mental imagery with synesthesia has been to use brain imaging techniques (e.g., DTI, PET, fMRI). Neurobiological research has attempted to elucidate the relationship between mental imagery, synesthesia, and perception by comparing the regions of cortical activation while participants evoked colored mental images or synesthetic color percepts. Generally, such studies have shown activation of visual areas for visual imagery as well as for synesthetic colors (in the absence of visual input for both cases), thus verifying the genuineness of these processes. For example, Nunn et al. (2002) used fMRI to determine whether synesthetic colors were more similar to color percepts or mental images of colors. Their participants were word-color synesthetes, for whom speech would produce color concurrents. While in the scanner participants listened to either spoken words or pure tones while their eyes were closed (note that pure tones do not elicit concurrents for these synesthetes). The synesthetes' showed activation in V4/V8 in the left hemisphere in response to speech, but not to the tones. This finding suggests that synesthetic color may be similar to color percepts. Similar results were subsequently reported by other researchers (e.g., Hubbard et al. 2005; Sperling et al. 2006). In another experiment, Nunn et al. tested whether imagining colors would activate the same brain regions as in word-color synesthesia. Controls memorized the distinct color that eight words evoked for synesthetes. Once they had learned these associations they were tested in the scanner. Controls were presented with each word and asked to think of the name of the color that had been paired with the word and then to imagine this color. After each scan, participants self-reported the percentage of trials for which they believed they had made accurate images. Controls

did not show activation in V4/V8, suggesting that color synesthesia is more similar to perception than mental imagery. Nunn et al. concluded that synesthetic color experience may not be attributable to either learned associations or to mental imagery.

Nunn et al.'s finding that color imagery by controls did not involve significant activity in color selective regions supported a previous report by Howard et al. (1998) who used fMRI to compare color imagery with spatial imagery. While in the scanner, participants were asked about the colors of common objects, such as: *Is a strawberry darker red than a raspberry*? Their questions were designed so that they could not be answered simply based on categorical color knowledge. After the experiment had been completed, participants reported that they had experienced vivid, color images in response to the questions. In another experiment, Howard et al.'s participants viewed colored and achromatic Mondrian displays in the scanner. Their results indicated that color perception included activation of area V4; however, color imagery did not.

However, Rich et al. (2006) questioned whether the control participants in Nunn et al. imagery condition were actually evoking images or merely recalling the color name that had been associated with the word. Rich et al. also suggested that Howard et al.'s analyses might not have enabled them to capture a slight change in V4 activation.

In order to reveal the neural correlates of both color mental imagery and synesthetic color, Rich et al. (2006) conducted two fMRI experiments with grapheme-color synesthetes and controls. In one experiment, participants viewed achromatic pictures of pairs of common objects; all items had canonical colors (e.g., a banana or a cob of corn). Participants reported which of the pair normally occurs in a darker color. This task was selected because it should force participants to rely on their color imagery as opposed to color names or associations. A control task was also included in which participants determined which of the two objects would be larger. Rich et al. found activation in V4 in the right hemisphere for the color imagery task for both synesthetes and controls. A second experiment was designed to reveal the neural activity underlying grapheme-color synesthesia. All participants viewed stimulus sets of four items and were to report which one temporarily vanished. There were two sets of stimuli including items that would trigger synesthesia; one set included letters that were colored to be the same as individual synesthetic colors, and a second included only grayscale letters. There was also a baseline set composed of grayscale rectangles. The synesthetic color tasks revealed activity in the left medial lingual gyrus, but only for the synesthetes. Rich et al. noted that this region is activated in tasks involving color knowledge; thus it may be that grapheme-color synesthesia involves the retrieval of color knowledge.

There is a large body of neuroimaging research on synesthesia (see Rouw et al. 2011 for a recent review), and there have been incompatible findings, although some of these contrasting results may be attributed to individual variability, differences in the types of synesthesia, and low statistical power due to the relatively small number of participants (Hubbard 2007). It is likely that a number of neural structures become activated in synesthesia. Of interest here is what we might conclude from research

directly comparing cortical activity for mental imagery and synesthesia. At this time results are uncertain because V4 activation has been reported for both imagined colors (e.g., Rich et al. 2006) and synesthetic colors (e.g., Nunn et al. 2002), but notably not within the same study.

10.9   Conclusions

Imagery and synesthesia share some features, being analog spatial mental representations of objects, but they are clearly distinct in prevalence and in controllability, synesthesia being involuntary, and perhaps in brain localization, although this latter point is not yet well established. Unlike perception, synesthesia is not veridical; it does not provide information about the state of affairs in the world. Imagery, however, provides both near-veridical remembrance of things past and entirely imaginary or dreamlike events. We conclude that synesthesia represents a distinct category of mental experience, not reducible to either perception or to one of the subcategories of imagery (dreams, imagination, sensory, memory, and so forth).

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Chapter 11
Visual Imagery in Haptic Shape Perception

Simon Lacey and K. Sathian

Abstract Many studies now suggest that the brain is not organized around discrete parallel processing of modality-specific inputs, but rather has a multisensory task-based organization. For example, many areas previously thought to be specialized for various visual tasks, such as motion detection or face processing, have been shown to be active during analogous tactile or haptic tasks. Here, we focus on the involvement of visual cortex in haptic shape perception and review the extent to which this reflects visual imagery. We discuss a model of visuo-haptic object representation in which the lateral occipital complex houses object representations that are flexibly accessible via top-down pathways involving object imagery for familiar objects or bottom-up pathways for unfamiliar objects.

Keywords Multisensory • Cross-modal • Functional magnetic resonance imaging • Lateral occipital complex

S. Lacey (✉)
Department of Neurology, Emory University School of Medicine,
WMB-6000, 101 Woodruff Circle, Atlanta, GA 30322, USA
e-mail: slacey@emory.edu

K. Sathian
Department of Neurology, Emory University School of Medicine,
WMB-6000, 101 Woodruff Circle, Atlanta, GA 30322, USA

Department of Rehabilitation Medicine, Emory University,
Atlanta, GA, USA

Department of Psychology, Emory University, Atlanta, GA, USA

Rehabilitation R&D Center of Excellence, Atlanta VA Medical Center,
Decatur, GA, USA

11.1 Introduction

It used to be thought that the brain processes sensory inputs in parallel, modality-specific streams, but an extensive literature on multisensory processing now suggests that this is not the case. For example, many cerebral cortical regions previously considered to be specialized for processing various aspects of visual input are also activated during analogous tactile or haptic tasks. In humans, the set of visual cortical regions known as the MT complex, which processes visual motion, is also activated by tactile motion stimuli, even when there is no explicit task (Hagen et al. 2002; Blake et al. 2004; Summers et al. 2009). Tactile texture perception activates visually texture-selective areas in medial occipital cortex (Stilla and Sathian 2008; Sathian et al. 2011) while the lateral occipital complex (LOC) is selective for shape during both visual and haptic perception (Amedi et al. 2001, 2002; Zhang et al. 2004; Stilla and Sathian 2008). By contrast, haptic face recognition was found to activate the left fusiform gyrus (even though faces were felt with the left hand), while visual face recognition activated the right fusiform gyrus (Kilgour et al. 2005), and there is little overlap between visually and haptically face-selective voxels in ventral and inferior temporal cortex (Pietrini et al. 2004). On the whole, however, the old consensus is giving way to the concept of a "metamodal" brain with a multisensory task-based organization (Pascual-Leone and Hamilton 2001; Lacey et al. 2009a; James et al. 2011a); for example, shape-selective regions respond whether the task is visual or haptic. An intuitively appealing idea is that the activation of classical visual regions during haptic perception reflects visual imagery (Sathian et al. 1997): when feeling an object, one naturally imagines what it might look like. However, this does not necessarily mean that visual imagery mediates visual cortical recruitment during haptic perception. In this chapter, we review the evidence concerning the potential role of visual imagery in haptic shape perception and outline a process model. By way of background, we begin with a review of the brain regions involved in visuo-haptic multisensory shape processing and the inferences that can be drawn from this evidence about the underlying representation of object shape.

11.2 Cortical Regions Involved in Visuo-Haptic Shape Processing

The principal cerebral cortical region involved in visuo-haptic shape processing is the LOC, an object-selective region in the ventral visual pathway (Malach et al. 1995). Part of the LOC responds selectively to objects in both vision and touch (Amedi et al. 2001, 2002). The LOC is shape-selective during both haptic 3D shape perception (Amedi et al. 2001; Zhang et al. 2004; Stilla and Sathian 2008) and tactile 2D shape perception (Stoesz et al. 2003; Prather et al. 2004). The LOC is thought to be a processor of geometric shape, since it is not activated during object recognition

triggered by object-specific sounds (Amedi et al. 2002) but does respond when auditory object recognition is mediated by a visual-auditory sensory substitution device (Amedi et al. 2007). Such devices convert visual shape information into an auditory stream, or "soundscape," conveying the visual horizontal axis through auditory duration and stereo panning, the vertical axis by varying auditory pitch, and brightness by varying loudness. Extracting shape information from these soundscapes, which requires substantial training, enables object recognition and generalization to untrained objects but only when individuals (whether sighted or blind) are trained using the specific algorithms involved and not when merely arbitrary associations are taught (Amedi et al. 2007). A more recent study required participants to listen to the impact sounds made by rods and balls made of either metal or wood (James et al. 2011b). Participants matched these sounds by the shape of the object that made them, the material of the object, or by using all the acoustic information available. The LOC was more activated when these sounds were categorized by shape than by material (James et al. 2011b). It is possible that such a matching task engaged visual imagery and that this could explain why these results differ from those obtained by Amedi et al. (2002). Taken together, these findings support the idea that the LOC is concerned with shape information, regardless of the input sensory modality.

Several parietal cortical regions also show multisensory shape-selectivity, including the postcentral sulcus (PCS) (Stilla and Sathian 2008), which is the location of Brodmann's area 2 in human primary somatosensory cortex (S1) (Grefkes et al. 2001). S1 is generally assumed to be purely somatosensory, but earlier neurophysiological studies in monkeys suggested that parts of S1 were visually responsive as well (Zhou and Fuster 1997; Iwamura 1998). Visuo-haptic shape-selectivity has also been widely reported in various parts of the human intraparietal sulcus (IPS), which is squarely in classical multisensory cortex. In particular, there are bisensory foci in the anterior IPS (aIPS) (Grefkes et al. 2002; Stilla and Sathian 2008); in the regions referred to as the anterior intraparietal area (AIP, Grefkes and Fink 2005; Shikata et al. 2008) and medial intraparietal area (MIP, Grefkes et al. 2004); and in the posteroventral IPS (pvIPS) region (Saito et al. 2003; Stilla and Sathian 2008) comprising the caudal intraparietal area (CIP, Shikata et al. 2008) and the adjacent, retinotopically mapped, areas IPS1 and V7 (Swisher et al. 2007). It should be noted that areas AIP, MIP, CIP, and V7 were first described in macaque monkeys, and their homologies in humans remain somewhat uncertain.

A crucial question about haptic or tactile activation of supposedly visual cortical areas is whether such activation is merely a by-product, with little or no functional relevance, or whether it is, in fact, necessary for task performance. Two lines of evidence indicate that the latter is the case. Firstly, neurological case studies indicate that the LOC is necessary for both haptic and visual shape perception. A patient with a left occipito-temporal cortical lesion, likely including the LOC, had both tactile and visual agnosia (an inability to recognize objects), although somatosensory cortex and basic somatosensory function were intact (Feinberg et al. 1986). Another patient with bilateral lesions to the LOC was unable to learn new objects either visually or haptically (James et al. 2006). Secondly, some studies have

employed transcranial magnetic stimulation (TMS) to temporarily deactivate specific, functionally defined, cortical areas. TMS over a parieto-occipital region activated during tactile discrimination of grating orientation (probable area V6 [Pitzalis et al. 2006]) interfered with performance of this task (Zangaladze et al. 1999). A recent study reported that repetitive TMS (rTMS) over left lateral occipital cortex disrupted object categorization while facilitating scene categorization (Mullin and Steeves 2011), suggesting that object processing cannot be carried out without a contribution from this area. Similarly, rTMS over the left aIPS impaired visual-haptic, but not haptic-visual, shape matching using the right hand (Buelte et al. 2008), but rTMS over the right aIPS during shape matching with the left hand had no effect on either cross-modal condition. The reason for this discrepancy is unclear and emphasizes that the exact roles of the PCS, the IPS regions, and LOC in multisensory shape processing remain to be fully worked out.

11.3   Visual Imagery or Multisensory Convergence?

An intuitively appealing explanation for haptically evoked activation of visual cortex is that this is mediated by visual imagery (Sathian et al. 1997). The LOC is certainly active during imagery: for example, the left LOC is active during mental imagery of familiar objects previously explored haptically by blind individuals or visually by sighted individuals (De Volder et al. 2001), and also during recall of both geometric and material object properties from memory (Newman et al. 2005). More pertinently, haptic shape-selective activation magnitudes in the right LOC were strongly predicted by individual differences in ratings of the vividness of visual imagery (Zhang et al. 2004). Some have argued against the visual imagery hypothesis on the basis that the congenitally blind show shape-related activity in the same regions as the sighted: since the congenitally blind do not have visual imagery, these researchers have argued that such imagery cannot account for the activations seen in the sighted (Pietrini et al. 2004). However, the fact that the blind cannot employ visual imagery during haptic shape perception is certainly no reason to exclude this possibility in the sighted, particularly given the extensive evidence for cross-modal plasticity in studies of visual deprivation (Pascual-Leone et al. 2005; Sathian 2005; Sathian and Stilla 2010). A further objection has been that the magnitude of activity in the LOC during visual imagery is only about 20% of that seen during haptic object identification, suggesting that visual imagery is relatively unimportant during haptic shape perception (Amedi et al. 2001; and see Reed et al. 2004). However, these studies generally did not monitor performance on the visual imagery task, and so the low activity in LOC during imagery could simply mean that participants were not performing the task consistently or were not maintaining their visual images throughout the imagery scan.

It is also important to be clear what is meant by visual imagery as this is not a unitary ability. Recent research has shown that there are two different kinds of visual imagery: "object imagery," i.e., images that are pictorial and deal with the actual appearance of objects in terms of shape, color, brightness, and other surface properties,

and "spatial imagery," i.e., more schematic images dealing with the spatial relations of objects and their component parts and with spatial transformations (Kozhevnikov et al. 2002; Kozhevnikov et al. 2005; Blajenkova et al. 2006; and see Chap. 16). This distinction is relevant because both vision and touch encode spatial information about objects—for example, size, shape, and the relative positions of different object features—such information may well be encoded in a modality-independent spatial representation (Lacey and Campbell 2006). Support for this possibility is provided by recent work showing that spatial, but not object, imagery scores were correlated with accuracy on cross-modal, but not within-modal, object identification for a set of very similar and previously unfamiliar objects (Lacey et al. 2007a).

In recent work, we investigated whether object and spatial imagery dimensions exist in haptic and multisensory representations, in addition to the visual domain (Lacey et al. 2011). We employed tasks that required shape discrimination across changes in texture and texture discrimination across changes in shape; these were performed both within-modally in vision and touch and cross-modally with visual study followed by haptic test, and vice versa. In both vision and touch, we found that shape discrimination was impaired by texture changes for object imagers but not spatial imagers, while texture discrimination was impaired by shape changes for spatial imagers but not object imagers. A similar pattern occurred in the cross-modal conditions when participants were accessing a multisensory representation (see Lacey et al. 2009b): object imagers were worse at shape discrimination if texture changed while spatial imagers could discriminate shape whether texture changed or not (Lacey et al. 2011). There is also evidence that early-blind individuals perform both object-based and spatially based tasks equally well (Aleman et al. 2001; see also Noordzij et al. 2007). Thus, it is probably beneficial to explore the roles of "object" and "spatial" imagery rather than taking an undifferentiated "visual" imagery approach. Moreover, the object-spatial dimension of imagery can be viewed as orthogonal to the modality involved.

An alternative to the visual imagery hypothesis is that incoming inputs in both vision and touch converge on a modality-independent representation, which is suggested by the overlap of visual and haptic shape-selective activity in the LOC (Amedi et al. 2001, 2002; Zhang et al. 2004; Stilla and Sathian 2008). While some researchers refer to such modality-independent representations as "amodal," we believe that this term should be reserved for linguistic or other abstract representations. Instead, we prefer use of the term "multisensory" to refer to a representation that can be encoded and retrieved by multiple sensory systems and which retains the modality "tags" of the associated inputs (Sathian 2004). The multisensory hypothesis is supported by studies of effective connectivity derived from functional magnetic resonance imaging (fMRI) data indicating the existence of bottom-up projections from S1 to the LOC (Peltier et al. 2007; Deshpande et al. 2008) and also by electrophysiological data showing early propagation of activity from S1 into the LOC during tactile shape discrimination (Lucan et al. 2010). However, both Peltier et al. (2007) and Deshpande et al. (2008) also found evidence for top-down projections, indicating that shape representations in the LOC may be flexibly accessible by either bottom-up or top-down pathways (see Sect. 11.4.2).

If vision and touch engage a common spatial representational system, then we would expect to see similarities in processing of visually and haptically derived representations; this, in fact, turns out to be the case. For example, the time taken to scan both visual images (Kosslyn 1973; Kosslyn et al. 1978) and haptically derived images (Röder and Rösler 1998) increases with the spatial distance to be inspected. Also, the time taken to judge whether two objects are the same or mirror-images increases nearly linearly with increasing angular disparity between the objects for mental rotation of both visual (Shepard and Metzler 1971) and haptic stimuli (Marmor and Zaback 1976; Carpenter and Eisenberg 1978; Hollins 1986; Dellantonio and Spagnolo 1990). The same relationship was found when the angle between a tactile stimulus and a canonical angle was varied, with associated activity in the left aIPS (Prather et al. 2004), an area also active during mental rotation of visual stimuli (Alivisatos and Petrides 1997), and probably corresponding to AIP (Grefkes and Fink 2005; Shikata et al. 2008). Similar processing has been found with sighted, early- and late-blind individuals (Carpenter and Eisenberg 1978; Röder and Rösler 1998). These findings suggest that spatial metric information is preserved in representations derived from both vision and touch and that both modalities rely on similar, if not identical, imagery processes (Röder and Rösler 1998). In addition, behavioral studies have shown that cross-modal priming is as effective as within-modal priming (Easton et al. 1997a, b; Reales and Ballesteros 1999) and that visuo-haptic cross-modal object recognition is subserved by a multisensory, view-independent, representation (Lacey et al. 2007a, 2009b; Lacey et al. 2010b; but see also Lawson 2009). Candidate regions for housing a common visuo-haptic shape representation include the right LOC and the left pvIPS, since activation magnitudes during visual and haptic processing of (unfamiliar) shape are significantly correlated across subjects in these regions (Stilla and Sathian 2008).

11.4 A Preliminary Model of Visual Imagery in Haptic Shape Perception and Representation

An important goal of multisensory research is to model the processes underlying visuo-haptic object representation. In pursuit of this, we recently investigated connectivity and inter-task correlations of activation magnitudes during visual object imagery and haptic perception of both familiar and unfamiliar objects (Deshpande et al. 2010; Lacey et al. 2010a). As a result, we are able to outline a preliminary process model of visual imagery in haptic shape perception that draws together the various findings reviewed above.

11.4.1 Activation Analyses

In one experiment (Lacey et al. 2010a), a visual imagery task required participants to listen to word pairs and to decide whether the objects designated by those words

had similar (e.g., snake-rope) or different (e.g., spoon-fork) shapes; responses were indicated by pressing buttons on a response box. Thus, in contrast to earlier studies, participants engaged in a task requiring visual imagery which could be verified by monitoring their performance. In a separate session, participants performed a haptic shape task in which they felt a series of unfamiliar objects with their right hand and made a same/different shape discrimination. Each of these tasks was paired with a suitable control task (see Lacey et al. 2010a, for details). We were particularly interested in brain areas that were activated in both the imagery and the haptic tasks and whether activation magnitudes in these overlap zones were correlated between the two tasks. Although there were four such overlap zones: in the LOC bilaterally, left aIPS, and left anteroventral IPS (avIPS), only the last showed a significant, positive inter-task correlation. These results therefore offered only weak evidence for the visual imagery hypothesis, perhaps reflecting only transient imagery of basic shape elements of the unfamiliar objects. However, while the haptic shape task involved unfamiliar objects, the visual imagery task obviously involved retrieving images of familiar objects from long-term memory. Reasoning that this mismatch in familiarity might have accounted for our findings, we conducted a second experiment in which the visual imagery and haptic shape tasks were exactly the same as before, except that we substituted a set of familiar objects in the haptic task. Thus, both tasks were now matched for familiarity. This yielded an extensive network of overlap zones, including bilateral LOC and a number of prefrontal areas. Not only were these regions active in both the imagery and haptic tasks but also activation magnitudes were significantly positively correlated between tasks in bilateral LOC, left pvIPS, ventral premotor cortex (PMv), inferior frontal gyrus (IFG), and the pulvinar/lateral posterior thalamic region (pul/LP). Thus, putting both experiments together, we demonstrated that while visual imagery was only weakly associated with haptic perception of unfamiliar objects, it was strongly linked to haptic perception of familiar objects. We should also note that the visual imagery and familiar haptic shape tasks probably engaged visual object imagery rather than visual spatial imagery (see discussion above). Participants in each experiment also completed the Object-Spatial Imagery Questionnaire (OSIQ: Blajenkova et al. 2006), and those with a preference for object imagery tended to be better at the familiar haptic task than those who preferred spatial imagery, while the reverse was true for the unfamiliar haptic task. This is consistent with the idea that haptic shape perception might differentially engage object and spatial imagery depending on familiarity (see Lacey et al. 2009a); however, the relationship between task performance and OSIQ scores in these experiments was fairly weak, and further investigation will be necessary to address these individual differences.

11.4.2 Effective Connectivity Analyses

Having found support for the visual imagery hypothesis, we then wished to place this on a stronger footing by examining the connectivity within the cortical networks involved in visual imagery and haptic shape perception (Deshpande et al. 2010).

In addition, examination of connectivity could distinguish between the visual imagery and multisensory convergence hypotheses. We had previously suggested that vision and touch share a common shape representation that is flexibly accessible via both top-down and bottom-up pathways (Lacey et al. 2007b). Visual imagery involves top-down paths from prefrontal and posterior parietal areas into visual cortex (Mechelli et al. 2004), and so, if LOC activity were mediated by visual imagery, we would expect to find similar, top-down paths into the LOC during both the visual imagery and haptic shape tasks. Alternatively, LOC activity might reflect convergence on a multisensory representation, in which case we would predict bottom-up pathways into the LOC from somatosensory cortex. The existence of paths relevant to both these possibilities was suggested by earlier studies of effective connectivity (Peltier et al. 2007; Deshpande et al. 2008), but these only employed unfamiliar objects and did not analyze task-specific connectivity.

In order to examine the effective connectivity between relevant brain regions, we employed Granger causality analyses. Briefly, causality can be inferred between two time series (in this case, activation magnitudes during the fMRI scan) by cross-prediction: if future values of time series $y(t)$ can be predicted from past values of time series $x(t)$, then $x(t)$ can be said to have a causal influence on $y(t)$ (Granger 1969) (for further details, see Deshpande et al. 2010). These analyses were carried out on a set of regions of interest selected to distinguish between top-down and bottom-up input into the LOC.

During visual imagery, the LOC was primarily driven top-down by prefrontal areas with significant inputs from the IFG and orbitofrontal cortex (OFC). There was a similar pattern during haptic perception of familiar shape, with top-down drive into the LOC from OFC and IFG. During haptic perception of unfamiliar shape, however, a very different pattern emerged, with the right PCS driving bilateral LOC as well as the left avIPS which, in turn, provided strong input to the left LOC. Thus, here bottom-up pathways from somatosensory cortex dominated LOC inputs. 2D correlations between the connectivity matrices for the three tasks showed that the visual imagery network was strongly correlated with the familiar, but not the unfamiliar, haptic shape network, whereas the two haptic networks were uncorrelated.

Based on these findings and on the literature reviewed earlier in this chapter, we proposed a conceptual framework for visuo-haptic object representation that integrates the visual imagery and multisensory approaches (Lacey et al. 2009a). In this model, the LOC contains a representation that is independent of the input sensory modality and is flexibly accessible via either bottom-up or top-down pathways, depending on object familiarity (or other task attributes). For familiar objects, global shape can be inferred easily, perhaps from distinctive features that are sufficient to retrieve a visual image, and so the model predicts important top-down contributions from parietal and prefrontal regions on the basis that haptic perception of familiar shape utilizes visual object imagery via these regions. By contrast, because there is no stored representation of an unfamiliar object, its global shape has to be computed by exploring it in its entirety. Haptic perception of unfamiliar shape may therefore rely more on bottom-up pathways from somatosensory cortex to the LOC. Since

parietal cortex in and around the IPS has been implicated in visuo-haptic perception of both shape and location (Stilla and Sathian 2008; Sathian et al. 2011), the model also predicts that, in order to compute the global shape of objects, these parietal regions would be involved in processing the relative spatial locations of object parts.

In a further test of the model, we recently compared visual spatial imagery to familiar and unfamiliar haptic shape perception (Lacey et al. 2012). Conjunction analyses showed parietal cortical foci common to spatial imagery and both haptic shape tasks as well as demonstrating inter-task correlations of activation magnitude. Spatial imagery performance was positively correlated with activity in multiple parietal cortical foci. These results suggest that spatial imagery appears to be implicated in haptic shape perception regardless of object familiarity, possibly related to assembling a global shape representation from component parts (Lacey et al. 2012).

11.4.3   Future Development

One goal for further work on this model is to examine how it relates to Kosslyn's model of visual imagery which proposes that visual images are maintained in a visual buffer and inspected via an "attentional window" (Kosslyn 1980, 1994). In this respect, it is interesting that we found inter-task correlations of activation magnitudes in IFG and the pul/LP thalamic area during visual object imagery and haptic perception of familiar shape. The IFG is involved in top-down generation and control of imagery processes (Kosslyn et al. 1993; Ishai et al. 2000; Mechelli et al. 2004) while the pul/LP thalamic area has been associated with shifts of attention within the visual buffer (Kosslyn et al. 1993; Kosslyn 1994). Since the imagery and haptic tasks both required a comparison between two stimuli in order to make the same/different decision, participants may well have shifted between images in making the comparison. At this stage, however, these relationships between our model and Kosslyn's (1980, 1994) can only be regarded as tentative, and a more principled investigation is required.

In addition, clearly objects are not exclusively familiar or unfamiliar, and individuals are not purely object or spatial imagers: these are dimensions along which objects and individuals may vary. Since these factors likely interact, with different weights in different circumstances, for example depending on task demands or individual history (visual experience, training, etc.), an individual differences approach is likely to be productive (see Lacey et al. 2007b; Motes et al. 2008).

11.5   Conclusions

In this chapter, we have reviewed evidence for the functional involvement of the LOC, a supposedly visual area, in haptic shape perception and outlined our model in which this involvement reflects visual object and spatial imagery, depending on

object familiarity. Both activation and connectivity analyses suggest that object imagery is associated with familiar, more than unfamiliar, objects while spatial imagery may be associated with both. Further work is required to examine individual differences as they relate to this model and to investigate how it interfaces with earlier models of visual imagery.

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Chapter 12
Auditory Imagery Contains More Than Audition

Timothy L. Hubbard

Abstract Contributions of nonauditory information to auditory imagery are examined. The spontaneous appearance of visual imagery concurrent with intentionally formed auditory imagery, and the similarities of spatial-temporal properties, mnemonic properties, and perceptual properties of auditory imagery and of visual imagery, is considered. A hypothesized distinction between an "inner voice" (which contains kinesthetic information related to speech articulation) and an "inner ear" (which does not) in auditory imagery is discussed, and evidence consistent (verbal transformation effect, judgments and comparisons of imaged content, clinical studies) and inconsistent (evidence against existence of a separate phonological loop, pre-articulatory auditory verbal imagery) with this distinction is considered. Possible relationships of auditory imagery to kinesthetic information from practice and performance of music and dance are considered, and the relationship of auditory imagery and synesthesia is briefly considered.

Keywords Auditory imagery • Subvocalization • Inner voice and inner ear • Kinesthetic imagery • Music and dance • Synesthesia • Visual imagery

12.1 Introduction

Much of everyday cognition involves multisensory imagery (Eardley and Pring 2006; Huijbers et al. 2011; Kosslyn et al. 1990; Shaw 2008). The discussion here considers multisensory or crossmodal components of auditory imagery (for discussion of auditory components of auditory imagery, see Chap. 4). Examples of auditory

T.L. Hubbard (✉)
Department of Psychology, Texas Christian University,
Fort Worth, TX 76132, USA
e-mail: timothyleehubbard@gmail.com

imagery that involve multisensory or crossmodal components include auditory imagery for music (e.g., if a pianist generates an auditory image of performing a piece of music, he or she might experience kinesthetic imagery of fingering the piano keys or visual imagery of the score in addition to auditory imagery of the notes) and auditory imagery for speech (e.g., if a person generates an auditory image of giving a speech, he or she might experience kinesthetic imagery of movements of the lips, tongue, or jaws or visual imagery of the audience or venue in addition to auditory imagery of the words). The relationship between auditory information and visual information in imagery is considered in Sect. 12.2. The distinction in auditory imagery between the inner voice and the inner ear is considered in Sect. 12.3. Possible relationships of auditory imagery to kinesthetic information involving body movements in practice and performance of music and dance are considered in Sect. 12.4. The relationship of auditory imagery to synesthesia is briefly considered in Sect. 12.5. Some conclusions are provided in Sect. 12.6.

12.2 Visual Imagery and Auditory Imagery

Halpern (1988a) noted that even though "representations of visual and auditory stimuli reflect modality specific differences, we can still examine some analogies between the two domains" (p. 434). However, Smith et al. (1995) noted "we cannot presume insights about visual imagery will simply generalize" (p. 1433) to auditory imagery. Two issues regarding such analogies and generalization are considered: if visual information results in spontaneous visual imagery concurrent with intentionally generated auditory imagery and if there are similarities between properties of visual imagery and properties of auditory imagery.

12.2.1 Spontaneous and Concurrent Visual Imagery

Intons-Peterson (1980) found that for a set of verbal descriptions of common everyday objects, participants reported that intentional generation of an auditory image was nearly always accompanied by spontaneous generation of a concurrent visual image, but that intentional generation of a visual image was accompanied by spontaneous generation of a concurrent auditory image only about half of the time. However, studies of auditory imagery do not usually query participants regarding visual imagery or report whether spontaneous visual imagery was experienced (e.g., Intons-Peterson 1992), and given that stimuli that are imaged often have multisensory or crossmodal components, it is possible that visual imagery is a common concomitant of intentionally generated auditory imagery. The automatic occurrence of concurrent visual imagery in Intons-Peterson (1980) is consistent with Godøy's (2001) suggestion that auditory images of sounds often evoke images (visual, motor, etc.)

regarding the object that emitted those sounds or how those sounds were produced.[1]

Schneider et al. (2008) presented participants with visual pictures of objects and recordings of different object sounds. Participants judged whether the recorded sound was appropriate to the pictured object, and responses were faster if the recorded sound was appropriate. If auditory information regarding the sound appropriate to a given pictured object involved imagery, then auditory imagery evoked by a visual stimulus might facilitate judgment of the recorded sound if the content of that image matched the content of the auditory percept. Similarly, a perceived or imaged sound might partially activate relevant visual information, and this might account for spontaneous visual imagery during generation of auditory imagery in Intons-Peterson (1980). However, Halpern et al. (2004) found that a visual imagery task suppressed activity in right secondary auditory cortex. Similarly, Azulay et al. (2009) found that a verbal memory or visual imagery task inhibited activity in auditory cortex in sighted individuals (see also Amedi et al. 2005), and they suggested that deactivation of irrelevant sensory cortices often accompanies generation of internal representations (see also Daselaar et al. 2010).

A greater likelihood of spontaneous visual imagery with intentional generation of auditory imagery than vice versa predicts a greater likelihood of deactivation of auditory cortex during visual imagery than of visual cortex during auditory imagery. If deactivation of sensory cortex for irrelevant modalities is greater for nonprimary sensory cortex, then primary visual cortex could be relatively active during auditory imagery (and spontaneous visual imagery relatively more likely), whereas primary auditory cortex would be relatively inactive during visual imagery (and spontaneous auditory imagery relatively less likely). Such a possibility is consistent with findings that auditory imagery is less likely to activate primary auditory cortex (e.g., Bunzeck et al. 2005; Halpern et al. 2004; Zatorre and Halpern 2005) than visual imagery is to activate primary visual cortex (e.g., Kosslyn et al. 1999; Slotnick et al. 2005). Also, visual information regarding an auditory stimulus is potentially more useful than auditory information regarding a visual stimulus, and so visual imagery might be more likely to accompany an auditory image than auditory imagery is to accompany a visual image.

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[1] Godøy (2001) argued "sound and sound source are inseparable in most cases of music cognition" (p. 242), but it could be suggested that his argument applies to auditory cognition more generally, especially given Bregman's (1990) suggestion that hearing evolved to inform listeners about stimuli in the environment. Visual or kinesthetic imagery of a sound source or how a sound was produced might aid in anticipating subsequent actions of or toward the sound source, and this would be consistent with theories that perception is influenced by possible action (e.g., Hommel et al. 2001; Proffitt 2006). On a related note, Baker (2001) argued that kinesthetic and visual imagery of the keyboard influenced composition of music during the past several centuries.

12.2.2   Shared Properties of Auditory Imagery and Visual Imagery

If visual information contributes to multisensory or crossmodal aspects of auditory imagery, then properties of visual imagery and properties of auditory imagery might be similar. Such similarities might involve spatial-temporal, mnemonic, and perceptual properties.

12.2.2.1   Spatial-Temporal Properties

Many temporal properties of auditory imagery appear to parallel spatial properties of visual imagery (for discussion, see Chap. 4). It takes longer to scan further across a visual mental image (Kosslyn 1980) or to mentally rotate an imaged object through a larger angular distance (Shepard and Cooper 1982). Similarly, it takes longer to scan through more beats of an imaged melody (Halpern 1988a, b; Zatorre and Halpern 1993; Zatorre et al. 1996) or count more syllables in an imaged string of letters (Aziz-Zadeh et al. 2005). If participants form an auditory image of the sounds made by each member of a pair of common environmental objects and then adjust the pitch or loudness of one member of the pair to match the pitch or loudness of the other member of the pair, participants require more time to make larger adjustments of pitch (Intons-Peterson 1992) and larger adjustments of loudness (Intons-Peterson 1980). However, it is not clear if similarities in properties of imaged visual space and imaged auditory time reflect properties of imagery per se (e.g., does the longer time to scan longer visual distances or longer temporal durations result from properties of visual imagery and auditory imagery or from properties of visual stimuli and auditory stimuli?).

Systematic covariation in performance on spatial tasks in visual imagery and on temporal tasks in auditory imagery can be observed. Douglas and Bilkey (2007) reported that individuals with amusia (i.e., severe difficulties in pitch discrimination) also performed poorly on visual mental rotation. They suggested that processing of pitch in music involves the same cognitive mechanisms used in processing spatial representations in other modalities. Cupchik et al. (2001) reported a positive correlation between performance on mental rotation and ability to detect whether a melody was played backward, and this demonstrated a relationship between the ability to manipulate (spatial) visual and (temporal) auditory information. The possibility that temporal processing of pitch in music involves the same cognitive mechanisms involved in spatial processing in visual stimuli is consistent with descriptions of auditory pitch in spatial terms (e.g., faster frequencies are "higher" and slower frequencies are "lower," Eitan and Granot 2006; Spence 2011) and findings that biases similar to those in representations of visual targets moving in visual physical space are found in representations of auditory targets moving in auditory frequency space (e.g., Fröhlich effect, representational gravity, Hubbard and Ruppel, in press).

Zatorre et al. (2010) acquired fMRI from musicians in a melody reversal task. Participants listened to the first few notes of a familiar melody or viewed the written title of that melody, and they judged whether a subsequently presented string of notes was an exact or inexact reversal of that melody. Participants exhibited increased activation in the intraparietal sulcus and in ventrolateral and dorsolateral frontal cortices (cf. Lotze et al. 2003). Mental rotation of visual stimuli activates the intraparietal sulcus (Zacks 2008), and Zatorre et al. argued that the melody reversal task provided an auditory analog of visual mental rotation, and furthermore, the intraparietal sulcus is involved in computations involving transformation of sensory input. A similar manipulation involving reversal of sequences of spoken word and nonword letter strings, and a similar pattern of cortical activation, was reported by Rudner et al. (2005). The same cortical structure appears to underlie transformations of visual images (through space) and transformations of auditory images (through time). In addition to the possibility that a single image could contain multisensory or crossmodal information, imagery might be multisensory or crossmodal in that specific types of image transformations in different modalities involve similar or the same cortical structures.

12.2.2.2 Mnemonic Properties

Visual imagery and auditory imagery can be used singly or in combination as mnemonic devices. Just as rehearsal of a visual stimulus using visual imagery can lead to improved retention (e.g., this addition is necessary for clarity and for parallel construction Bower 1970), so also can rehearsal of an auditory stimulus using auditory imagery (e.g., Keller et al. 1995). Indeed, rehearsal might be one of the primary functions of the inner voice in auditory imagery (MacKay 1992), and auditory imagery might provide an additional sensory code (Hubbard 2010). Curiously, both deaf and hearing participants exhibit benefits in recall in paired associate learning for words rated high in auditory imagery, although initial learning is more difficult for deaf participants (Heinen et al. 1976). Given that the inner voice involves kinesthetic information and auditory information (see Sect. 12.3), use of the inner voice in rehearsal would potentially involve use of multiple codes. Paivio's (1971, 1986) dual-coding theory suggests that memory for a stimulus would be enhanced if a sensory (visual) code is available in addition to a verbal code, and so it could be predicted that memory would be enhanced even more if multiple sensory codes (e.g., auditory, kinesthetic) are available.

Winnick and Brody (1984) presented participants with lists of words that were either high or low in both visual and auditory imagery or high in one and low in the other. If words were high in visual or auditory imagery, then instructions to form visual images or auditory images, respectively, resulted in better recall than if words were low in visual or auditory imagery, respectively. Similarly, Sharps and Price (1992; see also Sharps and Pollitt 1998) presented printed verbal labels, auditory

recordings, and visual pictures of stimuli. Recall was better if participants were presented with auditory recordings or visual pictures than verbal labels, and this was suggested to reflect use of auditory imagery and visual imagery as mnemonics. Also, recall was not influenced by whether participants were presented with auditory recordings, visual pictures, or combined auditory recordings and visual pictures. In both these studies, the effects of auditory and visual imagery were not additive, and use of combined auditory and visual imagery did not result in greater recall than did use of a single modality of imagery.

Tinti et al. (1997) examined whether an interactive imagery effect analogous to that in visual imagery (i.e., recall of an item cued by another item is enhanced if the two items are visualized as interacting, e.g., Kroll et al. 1986) could be found in auditory imagery. Participants were given verbal labels for pairs of objects, and they imaged the sound of each object. Sounds were either imaged as interacting (presented simultaneously from the same speaker) or noninteracting (presented sequentially from the same speaker). Recall was better in the interacting condition for both visual and auditory imagery than in a verbal elaboration condition, and this led Tinti et al. to suggest that interactive auditory imagery does not necessarily depend on articulatory mechanisms (see Sect. 12.3). Also, there was greater interference of (a) an interactive visual image with detection of a faint visual stimulus than a faint auditory stimulus and (b) an interactive auditory image with detection of a faint auditory stimulus than a faint visual stimulus. Such an interaction suggested different mechanisms for each modality rather than a single multisensory mechanism.

12.2.2.3 Perceptual Properties

There has been considerable discussion of the relationship of visual perception and visual imagery (e.g., Finke 1980, 1985; Kosslyn 1994; Shepard and Podgorny 1978). Initial examination of this relationship focused on behavioral and psychophysical evidence (e.g., Farah 1985), and recent examination focused on brain structures (e.g., Kosslyn et al. 2001; and see Chap. 2). Visual imagery can interfere with detection of a visual target (e.g., Craver-Lemley and Reeves 1992), auditory imagery can interfere with detection of an auditory target (e.g., Okada and Matsuoka 1992), and detecting a stimulus in a given modality interferes more with imagery in that modality than with imagery in another modality (Tinti et al. 1997). Such findings are usually interpreted as showing the limits of modality-specific processing: If resources are devoted to generating an image or perceiving a target in a specific modality, then fewer resources are available for perceiving a target or generating an image, respectively, in that modality (see also Segal and Fusella 1970). However, visual imagery can facilitate discrimination of a visual target (e.g., Finke 1986), and auditory imagery can facilitate discrimination of an auditory target (e.g., Hubbard and Stoeckig 1988). Similar effects of visual imagery on visual perception and of auditory imagery on auditory perception are consistent with similar or shared mechanisms for perception and for imagery across modalities, and this is consistent with spontaneous imagery of an expected stimulus or in a different modality.

12.3   The Inner Voice and the Inner Ear

In addition to perceiving sounds that are generated by stimuli in the environment, humans can perceive sounds that they generate, most commonly vocalization (e.g., speaking, singing). Just as generating vocalizations or listening to external sounds involve the voice or the ear, auditory imagery of vocalization or of external sound has been said to involve the "inner voice" or "inner ear," respectively. In this section, arguments for and against a distinction of the inner voice and the inner ear, the relationship of auditory imagery to reading, and the relationship of subvocalization to the distinction between the inner voice and inner ear, are considered in the context of Baddeley's model of working memory.

12.3.1   Baddeley's Model

In Baddeley's model of working memory (Baddeley 1986, 2000; Gathercole and Baddeley 1993), an executive is accompanied by several slave systems. One of these slave systems is involved in processing of auditory information and is referred to as the *phonological loop*. The phonological loop has two dissociable components: a phonological store subject to decay and interference and a subvocal articulatory rehearsal process that recodes nonarticulatory stimuli for the phonological store and refreshes decaying representations. Perception of irrelevant speech disrupts recall by interfering with the phonological store (Salamé and Baddeley 1982), whereas task-irrelevant articulation disrupts recall by interfering with rehearsal and with recoding of information for the phonological store (Baddeley et al. 1984). The phonological store and the articulatory rehearsal process have been equated with a passive inner ear and an active inner voice, respectively, in auditory imagery (e.g., Smith et al. 1995). Investigators examining auditory imagery have attempted to manipulate or limit effects of articulatory rehearsal by having participants image a nonvocal stimulus (e.g., Crowder 1989), chew candy, whisper or silently mouth words (e.g., Reisberg et al. 1989), chew gum (e.g., Halpern 1989), and clinch their jaws or vocalize other material (e.g., Smith et al. 1995).

12.3.2   Arguments for a Distinction of Inner Voice and Inner Ear

There are at least three types of arguments that could be used in support of a distinction of the inner voice and the inner ear within auditory imagery: the verbal transformation effect, judgments and comparisons of imaged stimuli, and clinical studies.

12.3.2.1 Verbal Transformation Effect

Reisberg et al. (1989) examined whether an analog of the verbal transformation effect occurred in auditory imagery. In the verbal transformation effect, a word or phrase that is continuously repeated is eventually parsed or segmented differently (e.g., a stream of rapid repetitions of the word "life" is eventually heard as a stream of rapid repetitions of the word "fly," Warren 1968). Reisberg et al. had participants image repeating the word "dress," and they examined whether those participants could "hear" the alternate parsing of "stress" in their images. The ability of participants to report the alternative interpretation decreased as subvocalization was increasingly blocked (by having participants vocalize, whisper, mouth the word but with no movement of air, image the word without mouthing, or clinch their jaws), and this suggested subvocalization contributed to (manipulation of) auditory imagery. Reisberg et al. suggested that their findings paralleled findings of Chambers and Reisberg (1985) that participants could not reinterpret a visual image without externalizing (drawing) that image, and Reisberg et al. suggested subvocalization was the auditory equivalent of externalization of the image.

Sato et al. (2006) examined the verbal transformation effect in speech and in imagery, and they considered differences in the timing relationships between different consonant clusters in the stimuli. Verbal transformation with repeated presentations occurred in speech and in imagery; however, the number and pattern of verbal transformations were reduced during imagery. Sato et al. found the same asymmetries in timing and consonant clusters in speech and in imagery, and they suggested that constraints originating from the motor system influenced the representation of verbal stimuli in the brain, even in the absence of an external auditory signal. Sato et al. suggested that their data pointed to articulatory constraints as the major factor during production, but they acknowledged that their results might reflect a multisensory representation that involved auditory and proprioceptive elements. Indeed, they suggested that the inner voice involved multisensory representation and that their findings supported a role for kinesthetic information in auditory imagery. The results of Reisberg et al. and of Sato et al. highlight how kinesthetic information regarding the voice influences auditory imagery even in the absence of external auditory information (see also Macken and Jones 1995; Smith et al. 1995).

12.3.2.2 Judgments and Comparisons

Smith et al. (1995) suggested that reinterpreting auditory images, parsing meaningful letter strings, and scanning familiar melodies all involved the inner voice and the inner ear. This conclusion was based on their finding that blocking subvocalization (i.e., interfering with the inner voice) and presenting concurrent irrelevant auditory material (i.e., interfering with the inner ear) each disrupted performance on each of those tasks. However, judgments of whether consonants were voiced or unvoiced involved the inner voice but not the inner ear, as blocking subvocalization disrupted judgments of voicing while concurrent irrelevant auditory material did not.

Judgments of pseudo-homophones (i.e., whether written strings of letters would sound like actual words if pronounced, e.g., aynjel, raynbo) did not appear to depend on the inner voice or the inner ear (i.e., were not influenced by blocking subvocalization or by irrelevant auditory material), but appeared to use a direct route from print to phonology. Although the inner voice and inner ear were both used on some tasks, there were other tasks in which one but not the other or neither was used. Smith et al. suggested that the inner voice and the inner ear were distinct structures or processes that worked in partnership but could be experimentally separated.

Evidence consistent with a contribution of kinesthetic information to the inner voice is found in brain imaging studies. Zatorre et al. (1996) reported a PET study in which participants compared pitches. Two words corresponding to lyrics from a well-known melody were visually displayed, and participants indicated whether the pitch of the second lyric was higher or lower than the pitch of the first lyric. In separate conditions, participants either listened to, or imaged hearing, the melody. In a control condition, participants saw pairs of written words and judged which word was longer. Activation patterns were similar in perception and imagery, and both differed from the control condition. Perception and imagery were associated with greater activation in secondary auditory cortices, frontal lobes, and left parietal lobe. Participants in the imagery condition exhibited increased activity in supplementary motor area (see also Lotze et al. 2003; Langheim et al. 2002). Zatorre et al. speculated that activity in motor areas resulted from participants subjectively rehearsing the lyrics, and this would be consistent with a role of subvocalization in auditory imagery.

Halpern and Zatorre (1999) used the same procedure as Zatorre et al., except they presented musical stimuli that did not contain verbal lyrics, and they predicted that subvocalization would not occur in the absence of verbal lyrics that could be vocalized. However, supplementary motor area was activated in auditory imagery, and it is possible that participants subvocally rehearsed the musical stimuli (e.g., by humming the approximate pitches of the stimuli) even though the stimuli did not contain lyrics. Halpern et al. (2004) examined perceived and imaged timbre of musical instruments. They predicted that imaginal comparison of such timbres should not involve subvocalization and so should not exhibit activity in supplementary motor area. However, weak (subthreshold) activity in supplementary motor area occurred during auditory imagery. Predictions in Halpern and Zatorre (1999) and in Halpern et al. (2004) that subvocalization would not occur in the absence of vocalizable stimuli appear to be based on Crowder's (1989) claim that subvocalization in auditory imagery of a stimulus would not occur if the sound of that stimulus could not be produced by a human vocal tract; however, findings in Halpern and Zatorre and in Halpern et al. were more consistent with Baddeley and Logie's (1992) claim that the articulatory loop was involved in rehearsal of nonvocal stimuli.

12.3.2.3   Clinical Studies

Auditory hallucinations might be hypothesized to reflect a failure to distinguish the inner voice from an external voice, but data on this are mixed (see also Chap. 4). Johns et al. (2001) reported that patients with auditory hallucinations were more

likely to confuse their voice with someone else's voice. Evans et al. (2000) gave tasks suggested by Smith et al. (1995) to involve the inner voice and/or the inner ear to patients with schizophrenia who were more or less prone to auditory hallucinations, and there were no differences between patient groups in task performance. McGuire et al. (1995) compared PET from patients with schizophrenia and control participants. If participants imaged their own voice, there were no differences between groups, but if participants imaged sentences in another person's voice, patients more prone to auditory hallucinations exhibited reduced activity in left middle temporal gyrus and rostral supplementary motor area (cf. McGuire et al. 1996; Shergill et al. 2000). However, methodological issues prevent such results from supporting a distinction of inner voice and inner ear (e.g., Hubbard 2010, noted that intentional imagery might not involve the same mechanisms as spontaneous hallucination; see also Linden et al. 2011).

12.3.3 Arguments Against a Distinction of Inner Voice and Inner Ear

There are at least two types of arguments that could be used against a distinction of the inner voice and the inner ear within auditory imagery: criticism of the Baddeley framework within which such a distinction is usually made and evidence that auditory verbal imagery might not depend upon articulation.

12.3.3.1 Criticism of Baddeley's Model

Human vocal articulatory mechanisms can produce only a limited range of sounds and timbres, and the majority of environmental sounds (e.g., rolling thunder, breaking glass, slamming door) cannot be produced by human vocal articulatory mechanisms. Consistent with this observation, Crowder (1989) and Pitt and Crowder (1992) suggested that a study of timbre in auditory imagery would allow a purer measurement of sensory aspects of auditory imagery; they suggested that because different instrumental timbres could not be produced by a human vocal tract, motor aspects of imagery would not be present in auditory imagery of instrumental timbre. Such an approach rejects the possibility that nonvocal or nonhuman sounds could be rehearsed by the articulatory rehearsal mechanism. One possibility would be to posit different types of rehearsal loop structures for different types of stimuli. Along these lines, and based on different degrees of interference in tonal memory caused by different types of stimuli, Pechmann and Mohr (1992) suggested that pitch might be rehearsed not by the phonological loop, but by a separate "tonal loop" (see Berz 1995, for a "musical memory loop"). However, such an approach needs principled constraints in order to prevent a proliferation of loop types.

In Baddeley's model, the phonological store and the articulatory rehearsal mechanism are relatively independent. An alternative view, the object-oriented episodic record (O-OER) model (Jones 1993; Jones and Macken 1993), suggests that all verbal events are represented in a similar way and that articulatory activity and irrelevant speech do not involve (or interfere with) different mechanisms. Macken and Jones (1995) suggest that a common assumption of Baddeley's model is incorrect, and they found that changing the content of irrelevant speech (from repetition of a single letter to repetition of a sequence of different letters) influenced the amount of interference. Importantly, effects of this "changing state" manipulation occurred if participants spoke the stimuli and (more weakly) if participants silently mouthed the stimuli. Macken and Jones also had participants vocalize, but auditory feedback from vocalization was masked by white noise. The absence of auditory feedback did not reduce the effect of vocalizing, thus suggesting that kinesthetic information alone could influence recall. Macken and Jones argued for a functional equivalence of codes from auditory, visual, and articulatory sources, and this would argue against a separation of structures such as in Baddeley's model.

12.3.3.2 Pre-articulatory Auditory Verbal Imagery

The idea that auditory imagery involves a separation of inner voice and inner ear appears to assume that auditory verbal imagery is generated solely by the inner voice. However, Oppenheim and Dell (2010) distinguish two classes of inner speech (i.e., auditory verbal imagery): the first is based on motor theories in which inner speech is as fully specified as actual speech and only lacks observable sound and movement, and the second is based on abstraction theories in which inner speech reflects activation of abstract linguistic representations and emerges before a speaker retrieves articulatory information. Oppenheim and Dell (2010) suggested that the presence of a lexical bias effect (i.e., speech errors resulting in words rather than in nonwords, e.g., Costa et al. 2006) but not a phonemic similarity effect (i.e., speech errors resulting in exchange of similar phonemes, e.g., Lukatela and Turvey 1990) in unarticulated (unmouthed) inner speech supports such a distinction (see also Oppenheim and Dell 2008). Tinti et al. (1997) found that recall of verbally elaborated words was decreased by an articulatory judgment task, whereas recall of aurally rehearsed words was decreased by a sound recognition task. Tinti et al. suggested that this difference demonstrated auditory imagery did not necessarily depend upon the phonological loop, and this is consistent with Oppenheim and Dell's view that inner speech could be pre-articulatory.

12.3.4   Reading

Material that is read is typically presented in a nonauditory modality but can usually be vocalized (e.g., spoken words, sung pitches). Thus, reading offers a venue to examine

the potential contribution of articulatory kinesthetic information to auditory imagery. Reading of two types of material, written text and musical notation, is considered.

12.3.4.1 Written Text

In an early review of the literature, McCusker et al. (1981) concluded that subvocalization was not necessary in reading. However, more recent findings suggest subvocalization is automatically evoked in at least some reading. For example, reading times are longer for "tongue-twister" sentences, suggesting that phonological representations are activated during visual reading and are similar to spoken representations (McCutchen and Perfetti 1982). Abramson and Goldinger (1997) measured lexical decision times to word stimuli, and responses were generally slower to phonetically long stimuli than to phonetically short stimuli, even if orthographic length of words was controlled. Alexander and Nygaard (2008) found that written passages attributed to a slow talker were read more slowly than were written passages attributed to a fast talker, and this difference was larger for difficult texts than for easy texts. The findings of Abramson and Goldinger (1997) and of Alexander and Nygaard (2008) suggest that auditory imagery does not reflect a "pure phonology," but instead reflects an "enacted phonology" involving kinesthetic information regarding pronunciation of word stimuli. In other words, auditory imagery of speech was influenced by kinesthetic information related to articulation.

Aleman and van't Wout (2004) examined whether subvocal rehearsal was a higher level cognitive process involving linguistic, but not articulatory-kinesthetic motor, processing or a lower level process involving only articulatory-kinesthetic motor processing. Participants were presented with written bisyllabic words and judged whether they would typically be pronounced with the stress on the first or second syllable. Additionally, participants completed a control task comparing the length of the written word to the length of a previously presented line. There were three interference conditions: articulatory suppression (i.e., counting aloud), finger tapping, and no interference. In judgments of stress, performance in the articulatory suppression and finger tapping conditions did not differ, but performance in the articulatory suppression condition was worse than in the no-interference condition. Also, articulatory suppression interfered with judgments of stress but not with judgments of length, whereas finger tapping interfered with judgments of length but not with judgments of stress. Aleman and van't Wout interpreted their data as reflecting the inner voice, and they suggested kinesthetic information regarding vocalization contributed to auditory imagery.

Aziz-Zadeh et al. (2005) applied repetitive transcranial magnetic stimulation (rTMS) to left hemisphere areas involved with speech processing and to homologous right hemisphere areas. Participants were visually presented with multisyllabic words that they spoke or imaged, and they reported the number of syllables in each word. Application of rTMS over the left hemisphere distorted speaking and imaging. Latencies were longer for left hemisphere anterior and posterior sites relative to

right hemisphere sites, and stimulation of right hemisphere posterior sites increased latency for speaking but not for imaging. Callan et al. (2006) acquired fMRI concurrent with singing, speaking, imaged singing, or imaged speaking. Their analyses focused on differences between singing and speaking rather than on differences between actual production or imaged production, but it appears that both actual production and imaged production involved activation of motor cortex. Indeed, Callan et al. suggested that their data "point toward a motor theory of music perception" (p. 1,339) similar to motor theories of language perception. The results of Aziz-Zadeh et al. and of Callan et al. are consistent with the presence of kinesthetic information in auditory imagery.

12.3.4.2   Musical Notation

Brodsky et al. (2003, 2008) presented musicians with a musical score consisting of a well-known melody embedded within a larger melodic context. Participants judged whether a subsequently played musical excerpt contained the melody embedded within the visual score, and they performed worse if score reading had been accompanied by phonatory interference (i.e., wordless humming of a folk melody) than by rhythmic interference (finger tapping of a steady beat while hearing an irrelevant rhythm) or if there was no interference. A follow-up experiment manipulated whether participants generated phonatory interference at the time of score reading. Detection of embedded melodies was worse if participants hummed during score reading, and there was no difference in detection if participants listened to a recording of their previous humming or if there was no interference. Brodsky et al. (2008) also found that EMG activity near the larynx was greater during reading of a musical score than during control tasks. These results were interpreted as suggesting that notational audiation (i.e., auditory imagery of music notated in a musical score induced by reading of that score) involves kinesthetic-like phonatory processes.

Repp and Goehrke (2011) presented pianists with ambiguous three-note melodies, the last two notes of which formed a tritone interval. Previous research had found that if each of the notes in a tritone interval was composed of harmonics spaced an octave apart, then some participants heard the interval as ascending in pitch, and other participants heard the interval as descending in pitch (e.g., Deutsch 1987; Repp 1997). Repp and Goehrke's participants played the notated melodies on a keyboard or viewed the musical notation while listening to the notes being played. Participants were more likely to hear the tritone as ascending or descending if the notation suggested that the tritone should be an ascending or descending interval, respectively, and this occurred regardless of whether participants actively played the notes or passively listened. Repp and Goehrke suggested that the musical notation influenced judgment of the ambiguous melodies and, more specifically, that auditory imagery arising from the visual musical notation might have influenced perception. However, whether auditory imagery was actually generated

was not assessed, and it seems possible the written notation itself (and keys pressed in the playing condition) could have biased judgment.[2]

12.3.5   Subvocalization and the Inner Voice/Inner Ear Distinction

As discussed here and in Hubbard (2010), many findings are consistent with a role of subvocalization in auditory imagery, and these findings include (a) a decrease in memory for verbal materials if auditory imagery is blocked (Aleman and van't Wout 2004), (b) interference of verbal processes with musical imagery (Weber and Brown 1986), (c) interference of phonatory processes with recognition of an embedded melody (Brodsky et al. 2003, 2008), (d) activation of cortical areas during auditory imagery that are also activated by tasks involving the phonological loop (Aleman et al. 2005), (e) activation of motor areas during auditory pitch and timbre imagery (Halpern et al. 2004; Zatorre et al. 1996), (f) increased laryngeal activity during notational audiation (Brodsky et al. 2008), and (g) the importance of subvocalization in reinterpreting an auditory image (Reisberg et al. 1989; Smith et al. 1995). However, some findings do not appear to require or involve a role of subvocalization in auditory imagery, including (a) judgment of pseudo-homophones (Smith et al. 1995), (b) effects of articulatory judgment on memory for verbally elaborated or imaged words (Tinti et al. 1997), and (c) pre-articulatory activation of abstract linguistic expressions (Oppenheim and Dell 2010). Subvocalization appears to be involved in many, but not all, examples of auditory imagery.

The importance of subvocalization in auditory imagery has been used to support the hypothesis of a separate inner voice and inner ear; however, it is not clear that use of subvocalization in auditory imagery actually requires a distinction between such structures. Although it is tempting to suggest that auditory imagery generated or manipulated by subvocalization involves the inner voice and that auditory imagery not generated or manipulated by subvocalization involves the inner ear, such a distinction does not consistently map onto the data (e.g., activation of supplementary motor area in judgments of instrumental timbres, Halpern et al. 2004; involvement of the articulatory loop in rehearsal of nonvocal stimuli, Baddeley and Logie 1992). Furthermore, if auditory imagery involves mechanisms used in perception or production of speech, it is not clear why those mechanisms would appear to have greater flexibility in content in imagery than in vocalization. Although the experimental data suggest that subvocalization influences auditory imagery, this issue is separable from whether such subvocalization involves (or requires) a distinction similar to the distinction between the inner voice and the inner ear.

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[2] As noted by Zatorre and Halpern (2005) and Hubbard (2010), some researchers suggest or claim a role for auditory imagery in accounting for a specific experimental outcome even if there was no evidence that imagery was actually generated and used in the experimental task. For the sake of completeness, studies that suggest a role for imagery are included in the current chapter, but it is noted if studies do not provide sufficient evidence auditory imagery was actually generated and used in the experimental task.

An important objection to the view that the inner voice and the inner ear are separate structures is based on motor theories of perception and on theories regarding the coupling of perception and action. More specifically, perception of another person's actions has been hypothesized to activate one's own action or motor plans (e.g., Knoblich and Sebanz 2006; Wilson and Knoblich 2005), and so if auditory imagery involves many of the same mechanisms as auditory perception (see Hubbard 2010), then articulatory mechanisms should be activated in auditory imagery of another person's speech (i.e., the inner ear) as well as in auditory imagery of an individual's own speech (i.e., the inner voice). Furthermore, if auditory imagery previously attributed to the inner ear includes articulatory information (as suggested by motor theories of perception), and if auditory imagery attributed to the articulatory loop does not necessarily include articulatory information (as suggested by rehearsal of nonvocal stimuli, Baddeley and Logie 1992), then the primary difference between the inner voice and the inner ear is eliminated (Hubbard 2010). Although useful as a heuristic, it is not clear if the inner voice and the inner ear are actually separate and distinct; data consistent with such a distinction might reflect differences in content or strategy rather than differences in structure or mechanism.

12.4   Nonvocal Kinesthesia and Auditory Imagery

Kinesthetic information arises from activities other than speech articulation (e.g., body motion while playing a musical instrument or in dance), and it is possible that kinesthetic information from such activities might influence auditory imagery (e.g., Palmiero et al. 2009, suggest that imagery in several modalities activates motor areas). The relationships of nonvocal kinesthetic information in music and dance to auditory imagery are considered.

12.4.1   Music

There are at least three ways that nonvocal kinesthetic information in music might influence or contribute to multisensory auditory imagery: formation or activation of action plans, similarities in actual musical performance and imaged musical performance, and use of imagery in mental practice.

12.4.1.1   Action Plans

Keller and Koch (2006) had musicians respond to different color stimuli by tapping different keys. The keys were arranged vertically, and color stimuli were flashed at a specific tempo that participants were instructed to match in their tapping. Tapping a key triggered an auditory tone unique to that key, and assignment of tones to keys was

compatible with musical pitch height (i.e., top, middle, and bottom keys associated with high, medium, and low pitches, respectively) or incompatible with musical pitch height. Timing of taps was more accurate in the compatible condition (see also Elkin and Leuthold 2011). Keller and Koch (2008) used a similar task and suggested that the compatibility effect reflected improvement in auditory imagery as a result of musical training. Keller et al. (2010) used a similar task and reported that timing was more accurate and movements were less forceful in the compatible condition. Keller et al. argued that a compatibility effect on the first tone indicated that anticipatory auditory imagery modulates temporal kinematics of an action sequence and that auditory imagery might benefit musical performance by enabling rapid and thorough action planning. However, none of the studies of Keller and colleagues provided independent evidence that auditory imagery was actually generated in the tasks.

Keller and Appel (2010) examined coordination of body sway and sound onsets in piano duets. Participants with high self-reported vividness of auditory imagery exhibited better coordination of keystrokes and body sway when performing (regardless of whether they were in visual contact), and Keller and Appel suggested that auditory imagery enhanced operation of internal models that simulated one's own actions and another's actions. This suggestion is consistent with the possibility that auditory imagery includes information regarding motor planning. Consistent with this, Pecenka and Keller (2009) reported that pitch acuity in auditory imagery and ability to synchronize in a tapping task were positively correlated and related to musical experience. Satoh et al. (2001) acquired PET while participants listened to motets involving four-part harmony. If participants focused on the harmony as a whole, then there was greater activation in bilateral temporal lobes, cingulate gyrus, occipital cortex, and medial surface of the cerebellum. If participants focused on the alto line, then there was greater activation in bilateral superior parietal lobe, bilateral precunei, and bilateral orbital frontal cortices. Satoh et al. suggested that differences in activation patterns reflected kinesthetic imagery based on motion of the pitch contour in the alto line.

12.4.1.2 Imaged Performance

Lotze et al. (2003) acquired fMRI of professional or amateur violinists who imaged a musical performance or made finger movements appropriate to a musical performance. Activation of somatosensory cortex of professionals was more focused in both actual and imaged performance, and self-reported vividness of imaged performance was higher in professionals. Auditory cortex was not activated during imaged finger movements. Lotze et al. speculated that musical training strengthened connections between auditory and movement areas of the cortex so that if one area was activated, the other area was also activated; however, such coactivation appeared to require either actual movement or actual auditory stimuli. The possibility of a connection between motor and auditory cortical areas is consistent with results in Mikumo (1994), who presented participants with novel melodies and found pitch encoding could be enhanced if participants made finger tapping movements as if

they were playing the melodies on a piano. Presumably, it was not the tapping per se, but the relative spatial locations of the taps (corresponding to relative locations of piano keys) that discriminated different pitches and aided encoding.

Meister et al. (2004) acquired fMRI from pianists presented with a musical score who either played it on a silent keyboard or imaged playing it. Post hoc questionnaires suggested that participants experienced "clear" and "reasonably vivid" imagery in both conditions. There was significant overlap of the areas of cortical activation in the silent keyboard and imagery conditions, with activations in primary sensorimotor cortex and premotor cortex. Activation of these areas was greater during performance on the silent keyboard than during imagery, but significant activation during imagery still occurred. Consistent with Lotze et al. (2003), there did not appear to be significant activation in auditory areas. However, it is not clear whether activation in Meister et al. reflects only the motor component of musical auditory imagery (i.e., imagery of finger movements) or is also related to auditory qualities of musical auditory imagery. There was also increased activation of intraparietal sulcus (cf. Zatorre et al. 2010), and this was suggested to relate to hand–eye coordination (Simon et al. 2002) or rhythm (Schubotz et al. 2000).

12.4.1.3 Mental Practice

Highben and Palmer (2004) examined auditory imagery and motor imagery in music practice. During practice, participants received (a) both auditory and motor feedback, (b) motor but not auditory feedback (silent keyboard), (c) auditory but not motor feedback (fingers held loosely while participants listened to a recording), or (d) neither auditory nor motor feedback. Participants then played the piece from memory. Performance was best if both auditory and motor feedback had been present during practice and worst if neither auditory nor motor feedback had been present. Participants with higher scores on a test of auditory imagery (involving memory for melodies) were less affected by a lack of auditory feedback during practice. Lim and Lippman (1991) had pianists practice unfamiliar pieces, and practice could consist of playing the piece, visually inspecting the score, or listening to a recording of the piece. Participants were encouraged to use visual, auditory, or kinesthetic imagery. Playing led to the best performance and visual inspection to the worst performance. The results of Highben and Palmer and of Lim and Lippman suggest that imagery might aid in music practice, but perhaps only if participants were proficient with imagery.

Cahn (2008) noted that previous studies of mental practice on music performance involved learning notated music, and he suggested that mental practice might be effective for other types of music performance such as jazz improvisation. Cahn had music students practice tonal patterns typical of those used in jazz improvisation. Practice was all physical, combined physical and mental (i.e., auditory and kinesthetic imagery) with physical practice during 66% or 33% of practice time, or all mental. There was no effect of practice type on pieces that were relatively easy,

but practice that was all or mainly physical led to better performance on more difficult pieces than did practice that was all or mainly mental. Theiler and Lippman (1995) had guitarists or vocalists practice musical pieces with physical practice, mental practice alternating with physical practice, or mental practice that was paired with a recording and alternated with physical practice. Mental practice alternated with physical practice led to the best performance, and Theiler and Lippman suggested that mental practice could facilitate coding and create optimal attention and arousal. The results of Theiler and Lippman and of Cahn suggest that mental practice can be effective in learning easier musical stimuli.

12.4.2 Dance

There are at least two ways that nonvocal kinesthetic information in dance might influence or contribute to multisensory auditory imagery: Auditory imagery might be directly related to some aspect of instruction, practice, or performance of dance; and auditory imagery might be related to dance via parallels between music and dance.

12.4.2.1 Imagery in Dance

Consistent with recent interest in embodied cognition (e.g., Barsalou 2008; Gibbs 2006), several recent papers considered the role of the body in music cognition (e.g., Dogantan-Dack 2006; Sedlmeier et al. 2011) and perception (e.g., Behne and Wöllner 2011; Juchniewicz 2008), and motion of the body has been hypothesized to underlie musical affect (Eitan and Granot 2006). Analogously, music cognition in the form of auditory imagery might influence the body in related activities such as dance. Movements of the body can parallel movements in music (e.g., both exhibit slowing near the end of a movement, as when runners slow before stopping and ritardandi occur at the end of a piece of music, e.g., Friberg and Sundberg 1999) and movements of the body in response to music (i.e., dance) can represent common (multisensory) elements related to rhythm, tempo, meter, and articulation (Fraisse 1982; Mitchell and Gallaher 2001). Although there have been studies of visual imagery and kinesthetic imagery in dance performance, instruction, and practice (e.g., Bläsing et al. 2010; Murphy et al. 2008), whether auditory imagery might influence kinesthetic information in dance, and vice versa, has received relatively little consideration.

In extensive studies of imagery on dance performance and instruction, Krasnow et al. (1997) examined effects of different kinds of imagery on dance training, and Nordin and Cumming (2005, 2006) reported that higher level dancers received more encouragement to use imagery and more instruction in using imagery than did lower level dancers. However, neither Krasnow et al. nor Nordin and Cumming addressed

auditory imagery, nor does auditory imagery appear to have been included in subsequent studies of dance. Given that imaged musical stimuli preserve perceptual (Intons-Peterson 1992) and emotional[3] (Lucas et al. 2010) qualities of stimuli, coupled with the structural similarity of music and dance (Krumhansl and Schenck 1997), relationships between kinesthetic imagery of dance and auditory imagery of music could be predicted. For example, given similarities of movement in auditory frequency space to movement in visual physical space (e.g., Eitan and Granot 2006; Hubbard and Ruppel in press), auditory imagery of ascending or high pitches might facilitate rising or sustained movement, auditory imagery of legato musical notes might facilitate smooth movements, and so on. Such predictions are consistent with findings that auditory stimuli can facilitate nondance body movements (e.g., Sabaté et al. 2008).

12.4.2.2 Music and Dance

Eitan and Granot (2006) had participants report whatever types of imaged motions of a human character were suggested by various types of musical stimuli. Different musical features resulted in different types of imaged motion (e.g., changes in pitch contour influenced imaged movement along axes of visual space). The mappings of musical features to different types of imaged human motion were not influenced by participants' level of musical training and so presumably reflected a fundamental aspect of representation. Krumhansl and Schenck (1997) had participants listen to a composition by Mozart, watch a dance choreographed to that music, or listen to the composition by Mozart while watching the choreographed dance. Participants made judgments of when sections ended, new ideas were introduced, and of tension and emotion. Responses in all participants were highly correlated, thus suggesting that kinesthetic information in the dance was as capable of conveying structural and expressive information as was the music. Consistency in imaged patterns of movement in Eitan and Granot, and similarities of responses to music and dance in Krumhansl and Schenck, suggests that there might be an overlap of information in auditory imagery of music and in kinesthetic imagery of dance.

This overlap was examined by Mitchell and Gallaher (2001). In some conditions, participants were presented with a musical composition or a dance, and they judged which of several subsequently presented dances or compositions, respectively, best matched these. In other conditions, participants were presented with a simultaneous dance and composition, and they rated how well the two stimuli matched. Participants generally matched each composition with the dance intended to express that com-

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[3] The relationship between emotion and imagery is considered in Chap. 19 in this volume, and so just a few points specific to auditory imagery are mentioned here. First, music is a promising venue for exploring the relationship of auditory imagery and emotion (for a review of music and emotion, see Juslin and Sloboda 2001; also Collier and Hubbard 2001; Gagnon and Peretz 2003; Schubert 2004). Second, emotional experience of music might be related to the ability of music to evoke spontaneous visual imagery (Juslin and Västfjäll 2008), and this has implications for multisensory and crossmodal imagery.

position. The results of Mitchell and Gallaher are consistent with those of Eitan and Granot (2006) and Krumhansl and Schenck (1997). Participants in Mitchell and Gallaher described using imagery for a previously presented stimulus if stimuli were presented sequentially, and similarities in composition-first and dance-first conditions suggest that auditory imagery of music and kinesthetic imagery of dance contained equivalent or overlapping information. As noted earlier, such information might involve aspects of motion (and change) common to audition and to kinesthesia such as rhythm, tempo, meter, and articulation.

12.5   Synesthesia and Auditory Imagery

Any examination of multisensory or crossmodal components of auditory imagery would be incomplete without at least a brief consideration of auditory imagery and synesthesia (for reviews of synesthesia, see Baron-Cohen and Harrison 1997; Cytowic 1989; Marks 1978; Robertson and Sagiv 2005). Synesthesia is considered to occur if a stimulus in one dimension or modality induces a systematic and idiosyncratic perceptual experience of a specific stimulus in a different dimension or modality (e.g., hearing a specific sound induces a visual experience of a specific color, e.g., Marks 1975). The relationship of synesthesia and imagery is considered in more detail in Chaps. 9 and 10, but two points relative to auditory imagery in synesthesia should be mentioned here. The first point is that synesthesia is usually not bidirectional (e.g., Mills et al. 1999; Ward et al. 2005, but see Cohen-Kadosh et al. 2005; Kadosh et al. 2007), and so cases in which an auditory stimulus elicits nonauditory imagery do not imply an equivalent nonauditory stimulus would elicit auditory imagery. The second point is that although visual imagery can evoke synesthesia (Spiller and Jansari 2008), there is not yet reported evidence that auditory imagery can evoke synesthesia.

Induced imagery in synesthesia tends to be visual, and stimuli that induce imagery in synesthesia tend to be auditory, tactile, or gustatory (Cytowic 1989). The reason for the prevalence of induced visual imagery in synesthesia is unknown, although Hubbard (2010) speculated that this might reflect the more general phenomenon of visual dominance. Examples in the synesthesia literature in which a nonauditory stimulus elicits auditory imagery (e.g., composer Jean Sibelius reported experiencing different musical chords in response to viewing different colors, Pearce 2007) are rare, but it is not known if the paucity of reports of auditory imagery induced in synesthesia is due to a limitation of synesthesia or due to a bias in reporting. Given multisensory and crossmodal components of auditory imagery discussed earlier, it seems unlikely there are structural limitations on induced auditory imagery in synesthesia. It is not clear why there might be a bias in reporting auditory imagery. One highly speculative possibility is that auditory hallucinations are often linked to psychopathology, and this association creates a stigma against reporting synesthesia that involves induced auditory (especially verbal) imagery. Also, addi-

tional semantic content of auditory verbal imagery might interfere more with daily tasks and thus result in a diagnosis of psychopathology rather than of synesthesia.

12.6 Conclusions

Auditory imagery can evoke or include visual or kinesthetic information regarding a stimulus, and auditory imagery and visual imagery exhibit similar spatial-temporal, mnemonic, and perceptual properties. One type of kinesthetic information present in at least some auditory imagery is articulatory information related to vocalization, and auditory imagery has been considered to involve an "inner voice" (that included vocal articulatory information) and an "inner ear" (that did not include vocal articulatory information). Although the distinction of the inner voice and the inner ear was consistent with early research, more recent research and theoretical development question whether such a distinction is useful or veridical. Vocal articulatory information is a critical component in many examples of auditory imagery, but the extent to which vocal articulatory processes are necessarily involved in encoding or imaging nonvocal auditory stimuli is not clear. Kinesthetic information related to body movements in music and in dance might contribute to or overlap with auditory imagery, and auditory imagery might contribute to or overlap with information regarding motor activities such as practice and performance in music and in dance. Although auditory information can induce synesthetic experience in nonauditory modalities, nonauditory information is less likely to induce auditory synesthetic experience. In general, auditory imagery contains and is influenced by information from multiple modalities and experiential domains.

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Chapter 13
Visual and Motor Mental Imagery After Brain Damage

Paolo Bartolomeo, Alexia Bourgeois, Clémence Bourlon, and Raffaella Migliaccio

Abstract This chapter presents evidence from brain-damaged patients relevant to the debate concerning the neural underpinnings of visual and motor mental imagery capacities. For visual mental imagery, the domains of object shape and color, orthographic material, and spatial imagery (imaginal neglect) are examined. Concerning motor imagery, evidence is reviewed from patients with locked-in syndrome and vegetative state, Parkinson's disease, vascular strokes, and limb amputations. Although both visual mental imagery and motor imagery have been postulated to draw on similar neural resources as the corresponding "actual" abilities (respectively, visual perception and motor acts), the available evidence from brain-damaged patients indicates that such a close correspondence only exists for motor imagery. Visual mental imagery, on the other hand, seems to rely on the activity of high-level visual processing. This possibility seems consistent with the proposed "active"

P. Bartolomeo (✉)
Inserm-UPMC UMRS 975, Brain and Spine Institute, Groupe Hospitalier Pitié-Salpêtrière, 47 Bd de l'Hopital, Paris, France

AP-HP, Groupe Hospitalier Pitié-Salpêtrière, Fédération de Neurologie, Paris, France

Department of Psychology, Catholic University, Milan, Italy
e-mail: paolo.bartolomeo@upmc.fr

A. Bourgeois
Inserm-UPMC UMRS 975, Brain and Spine Institute, Groupe Hospitalier Pitié-Salpêtrière, 47 Bd de l'Hopital, Paris, France

C. Bourlon
Service de Rééducation et de Réadaptation Fonctionnelle, Clinique Les Trois Soleils, Boissise le Roi, France

R. Migliaccio
Inserm-UPMC UMRS 975, Brain and Spine Institute, Groupe Hospitalier Pitié-Salpêtrière, 47 Bd de l'Hopital, Paris, France

Department of Psychology, Catholic University, Milan, Italy

character of imagery abilities, which would not necessarily require the functioning of sensory cortices devoted to the processing of external stimuli.

Keywords Visual mental imagery • Motor mental imagery • Brain damage

This chapter first deals with visual mental imagery, with particular reference to evidence acquired through the study of brain-damaged patients; afterwards, we review aspects of motor imagery. Other forms of mental imagery (e.g., auditory) are not discussed here.

13.1   Visual Mental Imagery After Brain Damage

Visual mental imagery is the faculty whereby a visual item can be revisualized from memory. As with other cognitive functions, brain damage can disrupt this ability. The first reported case of a relatively isolated deficit of mental imagery came under Charcot's observation in the Salpêtrière Hospital in Paris (Charcot and Bernard 1883). M. X used to experience particularly vivid visual mental images for object forms and colors, which he described as being as precise and glowing as reality itself. He used his ability as a mnemonic technique, until one day he found himself to be completely unable to recall forms and colors from memory. For example, he lost his ability to produce detailed drawings from memory or to precisely recall poems and letters by "reading" them in his "mind's eye." This deficit was relatively selective, being accompanied by only minor problems in reading and a slight decrease in color perception. There is no record concerning the potential presence of a brain lesion in M. X, but his reading problems in the absence of a more elementary visual deficit might suggest left temporal damage with sparing of the occipital cortex.

In the domain of cognitive neurosciences, visual perception and visual mental imagery have often been regarded as cognitive functions subserved by common mechanisms and neural substrates. According to an influential model, visual mental images are "displayed" on a visual buffer consisting of topographically organized areas in the occipital lobe, similar to visual percepts (Kosslyn et al. 2006). A single visual buffer, putatively located in the primary visual areas (V1), would be used "bottom-up" to display visual percepts or "top-down" to display internally generated images (Farah 1984).

This equivalence between visual imagery and visual perception was originally motivated by empirical evidence coming from experimental psychology. For example, in a famous experiment, Shepard and Metzler (1971) found that the time employed by normal individuals to mentally rotate an imagined object was proportional to the angle of rotation (Fig. 13.1). Similarly, Kosslyn (1980) showed that the time employed to mentally scan an image increases with the distance to be scanned.
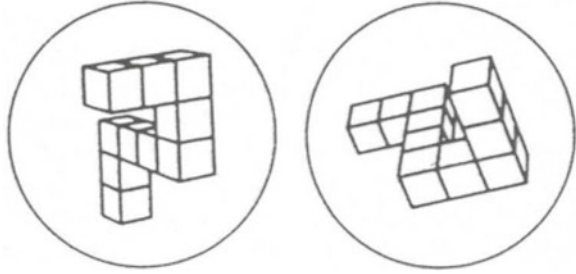
These findings were further substantiated by neuropsychological studies showing a frequent association of perceptual and imagery deficits in brain-damaged patients (Farah 1988). Together with results of neuroimaging experiments in normal subjects, this evidence prompted the conclusion that visual mental imagery, much as visual perception, depended on the functioning of retinotopic areas in the occipital lobe, including V1 (Kosslyn et al. 2006). However, since the 1990s other patient studies showing double dissociations between perception and imagery abilities (reviewed by Bartolomeo 2002) have produced a strong challenge to the perception-imagery equivalence hypothesis.

13.1.1 Visual Mental Imagery and the Striate Cortex

A first issue of interest concerns the role of V1 in visual mental imagery. Hypotheses postulating a large anatomo-functional overlapping between perception and imagery assign a central role to V1 in visual mental imagery (Kosslyn et al. 2006). If so, then V1 damage should impair visual mental imagery in patients with cortical blindness. However, neuropsychological studies have provided abundant evidence against this hypothesis. For example, Chatterjee and Southwood (1995) studied three cortically blind patients. Two of these patients had bilateral medial occipital damage but showed nevertheless an intact capacity for imagining object forms. In contrast, the third patient had damage extending from the occipital cortex well into the left temporal lobe and was unable to imagine object forms. More recently, another patient was described with complete and permanent cortical blindness after bilateral damage to V1, who had perfectly preserved visual mental imagery for objects, colors, and spatial relationships (Zago et al. 2010). In contrast, another cortically blind patient, who had signs of brain hypometabolism not only in the occipital cortex but also extending to the inferior and mesial temporal cortex, found himself unable to perform any tasks based on the visual appearance of places, symbols, objects, and animals (Policardi et al. 1996). Recently, Bridge et al. (2012) described a further patient with a lesion restricted to the gray matter of the calcarine sulcus (V1). Despite near-complete cortical blindness, this patient had vivid visual mental imagery. This patient also underwent fMRI, which demonstrated a pattern of cortical

activation during visual mental imagery in occipito-temporal extrastriate areas, and in parietal and frontal regions, which was indistinguishable from normal participants.

Altogether, this evidence is compelling in showing that lesions restricted to V1 do not typically produce deficits of visual mental imagery. A prediction stemming from the hypothesis of common V1 processes in visual perception and visual imagery is that unilateral occipital lesions producing lateralized visual field defects, such as homonymous hemianopia, should determine corresponding lateralized deficits in visual mental imagery, i.e., impaired imagery on the blind side of the visual field. Butter et al. (1997) described eight patients with unilateral field defects who were worse at recalling the location of previously presented dots on the blind side than on the normal side. The authors concluded that visual imagery involves topographically organized visual areas of the occipital lobe. However, there are several problems with this conclusion (see Bartolomeo 2002). There were no brain images for three of the patients; consequently, a lesion extending beyond the occipital cortex could not be excluded (such a lesion was indeed present in two of the remaining patients). One hemianopic patient performed the imagery task normally, contrary to the predictions of the perceptual/imagery equivalence model. Finally, even in the case of lesions anatomically restricted to the occipital cortex, functional damage may extend to other cortical areas, as functional brain imaging actually demonstrated in the previously mentioned case report by Policardi et al. (1996). A more direct challenge to the conclusions of the Butter et al. (1997) study came from the results of a more recent study (Dulin et al. 2011) conducted with similar methods as in the Butter et al. (1997). Dulin et al. found normal performance with lateralized mental images in 12 patients with homonymous hemianopia, six of whom had right-sided hemianopia and six left-sided hemianopia, i.e., they had no more difficulty imagining items in the contralesional hemispace than in the ipsilesional hemispace.

13.1.2 Visual Mental Imagery and Extrastriate Visual Areas

Even if visual mental imagery can bypass low-level visual areas such as V1, it could require the activity of visual areas at higher levels of processing in the ventral cortical visual stream, important for visual recognition (Milner and Goodale 1995; Mishkin et al. 1983). However, the precise level of visual processing putatively important for visual mental imagery remains uncertain. Bartolomeo et al. (1998a) described a striking dissociation between impaired perception for high-level visual attributes and preserved imagery in a patient (Madame D) with bilateral extrastriate lesions, at the borders between the occipital and the temporal lobes (see Fig. 13.3 below). After the occurrence of her lesions, Madame D became severely agnosic, alexic, achromatopsic, and prosopagnosic. However, her visual mental imagery for objects, words, colors, and faces was perfectly preserved. She produced plausible drawings from memory while being unable to identify her drawings on subsequent testing. Madame D had thus intact mental imagery for the very same visual entities

that she could not perceive. More recently, Moro et al. (2008) made a detailed report of the complementary dissociation in two patients with traumatic brain injury, who had impaired visual mental imagery with reasonably preserved perception. Furthermore, these two patients had spared auditory, gustatory, olfactory, and motor imagery. Tactile imagery was preserved in one patient. In both cases, there was extensive damage to the left temporal lobe in the absence of visible damage to the occipital cortex.

These and many other case reports (reviewed in Bartolomeo 2002) challenge the hypothesis that visual occipital areas are necessary to visual mental imagery and suggest instead that extensive damage to the left temporal lobe is crucial to observe deficits of visual mental imagery, at least for object shape and color and for orthographic material. Since this conclusion was proposed (Bartolomeo 2002, 2008), it has received further support from several more recent studies of patient with occipital damage and cerebral blindness (Bridge et al. 2012) or homonymous hemianopia (Dulin et al. 2011) (see Chap. 2 for a different take on the evidence from lesion studies of visual imagery). However, even if occipital cortex is not necessary to visual mental imagery abilities, higher level visual areas, rostral to the borders of the occipital lobe, might well be.

13.1.3 Visual Mental Imagery and Theories of Active Perception

In addition to various patterns of activation along the ventral cortical visual stream, fMRI studies of visual mental imagery have shown increased BOLD response in prefrontal and parietal regions (Mechelli et al. 2004). This is perhaps not surprising. Theories of perception are moving from views stressing the "reception" of external stimuli on relatively passive neural substrates (Hubel and Wiesel 1959; Marr 1982) to an emphasis on more active, exploratory processes of the organism (Ballard 1991; Di Ferdinando et al. 2007; O'Regan and Noë 2001). For example, the conscious experience of seeing is increasingly understood not only as the result of sensory processes but also as depending on active processes such as attentional orienting (see, e.g., Chica and Bartolomeo 2012). If so, then the "visual" character of mental imagery experiences, instead of requiring patterns of activity in early sensory areas, might be based on the "reenacting" of visual experiences through the use of active perception mechanisms (Thomas 1999), such as visual attention (Bartolomeo and Chokron 2002). Fronto-parietal networks are directly implicated in several attentional processes, such as orienting of spatial attention (see, for a recent review, Bartolomeo et al. 2012). Top-down activity from fronto-parietal networks might be essential to trigger visual imagery experiences through the activation of high-level visual areas in the temporal lobe.

In agreement with the hypothesis of an implication of attentional/eye gaze systems in visual mental imagery, a recent study (Bourlon et al. 2011b) confirmed that eye movements tend to follow similar paths during the exploration of a visual scene

and during retrieval of the same scene from long-term memory (see also Brandt and Stark 1997; Laeng and Teodorescu 2002, for similar results with visual scenes presented just before the imagery task).

The conclusion that occipital areas are unnecessary to visual mental imagery seems in contradiction with the results of many fMRI studies demonstrating increased BOLD response in striate cortex during imagery tasks, without any visual input (review in Kosslyn et al. 2006). One possibility to account for this discrepancy between lesion neuropsychology and functional neuroimaging is the following. Visual mental imagery is typically used in ecological settings to search for real objects (e.g., a pen on a cluttered desk). To perform visual search efficiently, one typically conjures up a mental image of the to-be-searched object (including, e.g., the shape and color of the pen I am searching for). Thus, even if V1 activity is not necessary to experience mental visual images (as demonstrated by cerebrally blind patients' preserved abilities of visual imagery), V1 may well be primed by the attentional system during visual mental imagery. Consistent with this hypothesis, a recent fMRI study (Langner et al. 2011) found increased BOLD responses in primary and secondary sensory areas when participants expected to perceive a stimulus in a specific sensory modality, in the absence of actual stimulus presentation.

13.1.4 *Domains of Visual Mental Imagery*

Visual mental imagery is not a unitary, undifferentiated faculty. Neuropsychological studies have demonstrated that it is possible to distinguish at least five kinds of visual entities whose imagery can be independently affected by brain damage: shapes of objects, colors of objects, faces, orthographic material, and spatial relationships (Goldenberg 1993). We will present here a selection of evidence concerning the neuropsychology of mental imagery for three of these domains: color, orthographic material, and spatial arrays.

13.1.4.1 Visual Mental Imagery of Color

Color processing is a privileged domain for the study of visual imagery abilities, because it has more chances of requiring genuinely visual processes than the other domains, whose spatial characteristics may allow the use of nonvisual strategies (Farah 1988) [note that the nonspatial character of color processing does not necessarily imply that it is independent of the attentional/eye movement system; on the contrary, given the inhomogeneous distribution of cones on the retinal surface, eye movements may well exert some influence on color perception (Bompas and O'Regan 2006)].

After several early reports of patients with an association of cerebral achromatopsia and loss of color imagery (see Damasio 1994), further case descriptions pointed out the possibility of normal color imagery in achromatopsic patients, and

of normal color vision with loss of color imagery (review in Bartolomeo 2002). For example, soon after her strokes Madame D (Bartolomeo et al. 1997) complained that she saw the world in shades of gray or, later on, in reddish-brown nuances. Nevertheless she could still form vivid mental images of colors and even perform subtle hue discriminations between imagined colors. Miceli et al. (2001) made a detailed report of patients PCO and IOC, with normal color perception but impaired color knowledge. These patients could not attribute the correct color to objects or select the correct crayon to color them. Of note, IOC, but not PCO, had apparently normal knowledge of the form and function of objects. Although the issue of mental imagery was not explicitly addressed in this study, the pattern of performance of these two patients strongly suggests a selective deficit of visual mental imagery for colors for IOC and an impairment of color and form imagery for PCO. PCO had suffered from encephalitis resulting in bilateral lesions (more extensive on the left than on the right) of the temporal pole and the inferolateral temporal regions (middle and inferior temporal gyri), dorsolateral prefrontal cortex, and orbital gyri. Damage was less extensive in the parietal lobe and the superior-rostral insula. Both hippocampi were atrophic. IOC had lesions in the calcarine cortex, the lingual gyrus, the isthmus and the adjacent cingulated gyrus, the parahippocampal gyrus, and the rostro-medial part of the fusiform gyrus, including part of the ventral portion of the temporal pole, with left hippocampal atrophy, as a consequence of a stroke in the territory of the left posterior cerebral artery (Fig. 13.2).

Interestingly, a control patient reported in the same study, SLA, who had more posterior lesions in the left hemisphere involving the posterior part of the lingual gyrus, the cuneus, and the calcarine cortex, had right homonymous hemianopia but no cognitive impairment. Thus, an extensive damage of the left temporal lobe, and particularly of its mesial part, seems both necessary and sufficient to produce deficits of color imagery.

13.1.4.2   Visual Mental Imagery of Orthographic Material

Literacy induces peculiar modifications of the visual system (Dehaene et al. 2010). In literate people, left posterior brain damage can disrupt the processing of visually presented letters and words in the relative absence of other deficits (and notably, with preserved writing), a disorder known as pure alexia (Bachoud-Lévi and Bartolomeo 2003; Dejerine 1892). We have already mentioned the case of Madame D, who, despite being profoundly alexic and incapable of identifying even single letters without errors (Bartolomeo et al. 1998b), was able to perform at ceiling difficult tests concerning the visual appearance of letters and words (Bartolomeo et al. 1998a). For example, she could easily answer questions such as: Take the letter M. Cut it in half vertically. Discard the right half and turn the left half upside down (the answer is V). A similar dissociation between impaired perception and preserved imagery also held for numbers in this patient. For example, Madame D was unable to recognize visually the number 6 but described it as "a half circle open toward the right, making a loop at its bottom." Complementary evidence concerning the neural bases of visual knowledge of orthographic material came from the description of another pure alexic patient, VSB (Bartolomeo et al. 2002). In addition to his reading deficit, VSB was found to suffer from a selective deficit for visual mental imagery of orthographic material, or loss of letter shape knowledge. In this patient, an extensive left temporal–parietal lesion (Fig. 13.3) severely impaired reading, whereas writing was relatively preserved.

At variance with other pure alexic patients described in the literature, VSB claimed to have become unable to mentally visualize letters and words. Indeed, his performance on a series of tests tapping visual mental imagery for orthographic material was severely impaired. However, allowing VSB to trace each item with his finger dramatically ameliorated performance on the same tests. Visual mental imagery for non-orthographic items was comparatively spared. The pattern of dissociation shown by VSB between impaired visual mental imagery and relatively preserved motor-based knowledge for orthographic material lends support to the view that separate codes, respectively based on visual appearance and on motor engrams, may be used to access knowledge of the visual form of letters and words.

Damage to domain-specific regions (Kanwisher 2000) or circuits (Epelbaum et al. 2008) in the ventral temporal lobe might thus contribute to the occurring of selective deficits of distinct domains of visually based knowledge. However, it remains uncertain whether there is a strict overlapping of perceptual and imagery functions within the same high-level visual regions in the temporal lobe (see, e.g., Rich et al. 2006), or whether nearby but distinct regions are important for these different abilities.

13.1.4.3   Imaginal Neglect

A particular class of deficits of spatial imagery concerns the impaired ability to conjure up or describe fully an imagined scene. Patients with damage to the right hemisphere may behave as if the left part of the world does not exist anymore, thus

Madame D   Patient VSB
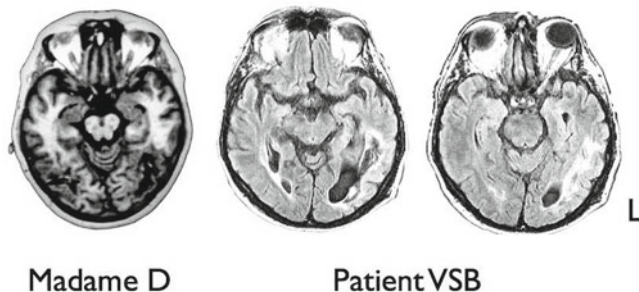
Fig. 13.3 Comparison between brain lesions in Madame D (Bartolomeo et al. 1998a, b) and in patient VSB (Bartolomeo et al. 2002). Madame D suffered from severe perceptual reading problems but no impairment in visual imagery of letter, words, or numbers. Patient VSB showed instead an association of impaired reading and impaired knowledge of the visual form of orthographic material. Note the rostral extension of the lesion in the left temporal lobe in VSB, in contrast to Madame D's more caudal lesions at the borders between the occipital and the temporal lobes. (L = left)

showing signs of left visuospatial neglect (Bartolomeo 2007; Halligan and Bartolomeo 2012) (Fig. 13.4).

About a third of these patients may also show neglect for the left part of their mental images (Bartolomeo et al. 1994). These patients may omit to mention the left side of the mental space when describing places from memory (Fig. 13.5), thus demonstrating "imaginal" neglect (Bisiach and Luzzatti 1978). Not all patients with visual neglect show imaginal neglect, perhaps because imagined details on the ipsilesional side of space have less attention-capturing power than real ones (Bartolomeo et al. 1994). Imaginal neglect can also occur in the absence of signs of perceptual neglect, either at onset or, perhaps more commonly, as a result of selective compensation for the perceptual aspects of the syndrome. Patients often learn with time (and possibly the help of people around them) to explore more thoroughly their visual environment. However, compensation may be more difficult to obtain in the more abstract imaginal domain, which is rarely the object of rehabilitation or of more informal reminders to "look to your left" (Bartolomeo and Chokron 2001). Thus, similar to other domains of visual mental imagery, several studies have reported the existence of double dissociations between imaginal and perceptual neglect (Anderson 1993; Beschin et al. 1997; Coslett 1997; Guariglia et al. 1993; Ortigue et al. 2001).

However, the study of imaginal neglect raises peculiar methodological problems. Often, very different task is used to evaluate spatial perception and spatial imagery. In particular, in several studies paper-and-pencil tests were used for perception whereas description from memory was used for imagery (Rode and Perenin 1994; Rode et al. 2007). Description from memory might rely more on verbal semantic memory than on visual imagery, and thus produce symmetrical descriptions even in the presence of imaginal neglect (Rode et al. 2004). To encourage the use of a visual mental strategy, a response time "geographical" test was devised (Bartolomeo et al. 2005), with strictly comparable perceptual and imaginal conditions (Bourlon et al.
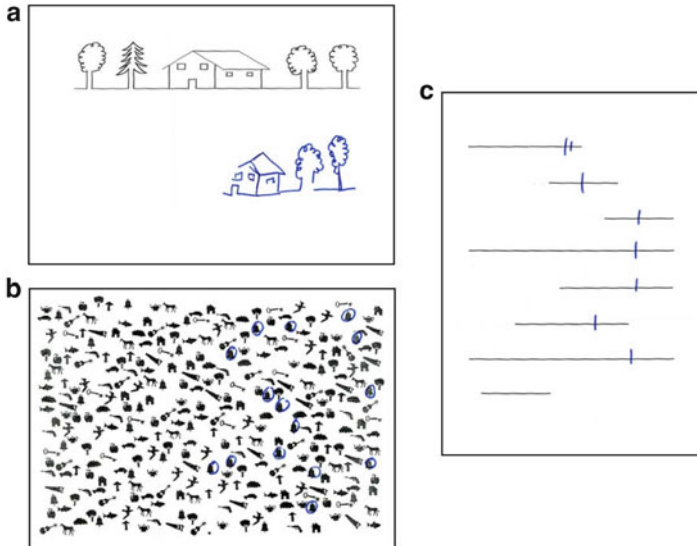
Fig. 13.4 Performance of a patient with left spatial neglect on paper-and-pencil tests. (**a**) copy (*below*) of a drawing (*top*) with omission of left-sided elements; (**b**) target cancellation task, with omission of left-sided targets (bells); (**c**) bisection of horizontal lines, with rightward deviation of the bisection mark and complete omission of one left-sided line

Fig. 13.5 In their seminal paper, Bisiach and Luzzatti (1978) reported two left neglect patients who, when asked to imagine and describe from memory familiar surroundings (the Piazza del Duomo in Milan), omitted to mention left-sided details regardless of the imaginary vantage point that they assumed, thus showing imaginal neglect. Patients had to imagine themselves in two different locations at opposite ends of the Piazza, and they omitted different buildings depending on where they imagined standing, thus showing that they retained memory of all of the buildings; as a consequence, their performance could not be ascribed to a purely mnestic impairment

2011a; Bourlon et al. 2008). In different tasks, participants either saw towns/regions on a map of France or heard their names, and pressed one of the two keys according to the stimulus location (left or right of Paris). The results obtained with these tasks confirmed the relative rarity of imaginal neglect with respect to perceptual neglect (about one-third of patients with perceptual neglect in Bartolomeo et al. 1994).

In a recent case report of imaginal neglect (Rode et al. 2010), structural and diffusion MRI demonstrated damage to several white matter tracts in the right hemisphere and to the splenium of corpus callosum. The same study reported on a second right-brain-damaged patient, who showed signs of perceptual but not imaginal neglect, and had damage to the same intrahemispheric tracts; the callosal connections, however, were spared. Imaginal neglect may thus result from the association of fronto-parietal dysfunction, which impairs orienting toward left-sided items (see Bartolomeo et al. 2007) and an additional posterior callosal disconnection, which prevents the symmetrical processing of spatial information from long-term memory.

In clinical settings, drawing from memory is often used to assess imaginal abilities and then directly compared to copying of drawings. However, the visual feedback in drawing tests may influence the patient by inducing an attentional capture of the right-sided details the patient had just drawn (Chokron et al. 2004). To address this issue, drawing without visual feedback was proposed, e.g., while blindfolded (Chokron et al. 2004) or using a pen which leaves no visible traces on the sheet (Cristinzio et al. 2009). While in general patients show more neglect with visual feedback than without visual feedback (Chokron et al. 2004), thus confirming the attention-capturing effect of right-sided visual items (Bartolomeo et al. 1994), one recent case report (Cristinzio et al. 2009) showed the opposite effect, perhaps as a consequence of a working memory impairment. To summarize, one possibility to account for the rarity of imaginal neglect is that this form of neglect might depend on deficits of top-down processes, such as endogenous attention or active rehearsal of spatial knowledge, that are less impaired than exogenous attention in patients with perceptual neglect (Bourlon et al. 2011a).

13.1.5   Assessment of Visual Mental Imagery

How to test for visual mental imagery abilities in brain-damaged patients? The usual strategy, borrowed from experimental psychology studies in normal individuals, is to ask patients to perform tasks that most likely cannot be resolved with simple access to (nonvisual) semantic information. For example, when exploring visual knowledge of colors, one can ask questions about the typical color of objects, with the precaution of avoiding those items whose color can be retrieved by using nonvisual knowledge (e.g., red/blood, white/snow) (Bartolomeo et al. 1997; Beauvois and Saillant 1985). A recent case report (Zeman et al. 2010), however, raises the disquieting possibility that at least some of these tasks can be correctly performed in the absence of a corresponding "quasi-visual" phenomenological

experience. These authors described a patient who performed normally on mental imagery tasks while denying that he experienced visual mental images. During attempted imagery, this patient, who had no visible brain lesion, showed reduced fMRI activation in a network of posterior regions, while activity in frontal regions was increased compared to controls. A possible conclusion could be that V1 activity is crucial to the phenomenological qualities of mental imagery. However, this conclusion is prevented by the recent description of a patient with V1 damage, who did report experiencing vivid visual images of faces and houses, and demonstrated extrastriate and frontal activations on fMRI (Bridge et al. 2012).

13.1.5.1 The BIP

A standardized paper-and-pencil battery of tests has recently been developed in order to assess perceptual and imaginal deficits in patients with brain damage (Batterie Imagination et Perception [BIP], Bourlon et al. 2009). The BIP, which currently exists in French (Bourlon et al. 2009) and Italian (Antonietti et al. 2008) versions, examines different domains of visual mental imagery and visual perception abilities such as object form and color, animals, orthographic material, numbers, faces, and spatial relationships. It comprises two parts: one composed of 14 tests assessing mental imagery, and another composed of 8 tests assessing various visual perceptual abilities. The BIP was designed to investigate associations and dissociations between perceptual and imaginal deficits in patients and thus provide evidence relevant to the debate concerning the neural bases of visual mental imagery. The imagery part of the BIP is composed of tests assessing the shape, size, or color of objects, animals, or orthographic material (letter and words) recalled from long-term memory and spatial relationships of visually presented items recalled from short-term memory. The BIP perception section consists of analogous tests, but with stimuli visually presented to the participants. The scope of this section is to allow a comparison as direct as possible between perception and imagery of similar visual entities.

13.2 Motor Imagery After Brain Damage

Motor imagery can be defined as a dynamic state of mind during which we can mentally simulate a given action. This type of phenomenal experience implies that the subject feels him/herself as performing the action, and it can be considered a kind of internal rehearsal. In order to do that, information about a motor act has to be processed from long-term memory to working memory. Within this framework, motor representations can be considered as the central core of the motor act. Interestingly, similar temporal durations have been observed when healthy subjects perform the same movements either actively or mentally (Jeannerod 1994).

This finding has been suggested to imply an activation of general motor processes for mental simulation as well. Moreover, when subjects were asked to describe how to make a given act without physically performing the actions, they often report that the images are experienced as a series of steps, like photographic stills (or snapshots) (Annett 1995). The reported imagery is often highly detailed, suggesting that it is based on specific memories. Motor imagery is often considered to be based on kinesthetic and visual imagery from a first-person perspective. However, participants find it quite easy to generate a third-person perspective, even if the "embodied nature" of an imagined motor act is stronger from a first-person perspective (Fourkas et al. 2006; Lorey et al. 2009; see also Chaps. 6 and 17 for discussions of perspective). For this reason, the third-person perspective cannot be considered as being part of motor imagery because of the loss of the feeling that the participant is actually performing the movement at that moment in time.

Functional correspondence between action and imagination goes beyond simple movements. For instance, the overlap of visuomotor transformation/motor movements planning and music processing emphasizes multimodal properties of cortical areas involved in motor imagery and complex skills such as music performance in pianists (Meister et al. 2004).

13.3   Neuroanatomical Correlates

From an anatomical point of view, a central idea is that a neural motor network is activated while imaging motor actions (Jeannerod 2001). Since the first step (the conceptualization of the act per se) of an action, real or imagined, is supposed to be the same, motor imagery depends on the activation of many of the same brain areas implicated in the executive motor system. Neuroimaging fMRI studies have revealed similar patterns of cortical (frontal and parietal) and subcortical (basal ganglia and cerebellum) activation during motor imagery and motor execution (Gerardin et al. 2000).

In particular, primary motor cortex (M1) is almost certainly involved with motor imagery, because patients with lesions in motor cortex imagine their movements as being slowed, consistent with the perceived slowness of real movements made by their contralesional limbs. M1 involvement during motor imagery is also reported in studies with amputees (Ersland et al. 1996) and in patients with spinal cord injury (Alkadhi et al. 2005).

In this framework, an inhibition of the efferent command is a prerequisite for motor imagery, because it prevents the movement from being executed. It has been repeatedly shown, by using different methods, that motor imagery may influence spinal excitability (Gandevia et al. 1997; Li et al. 2004). During motor imagery, a significant but subthreshold signal may be generated by M1 that produces changes of excitability at the spinal level.

Moreover, in agreement with the so-called simulation hypothesis (Jeannerod 1994), motor imagery activates an extensive cortical network including M1 and the secondary motor areas, such as premotor cortex (PMC), supplementary motor area (SMA), and parietal cortices (Sirigu et al. 1996).

It is commonly thought that the SMA plays a critical role in motor imagery. However, some studies report that the locations of SMA activity for motor imagery and motor execution overlap only partially (Deiber et al. 1996; Stephan et al. 1995). This may suggest that only some parts of the SMA play a specific role in motor imagery. Based on fMRI data sets acquired with very high temporal resolution during motor execution and imagery, Dynamic Causal Modeling was used to determine effective connectivity measures between SMA and M1 (Kasess et al. 2008). The results highlighted the importance of the SMA not only for the preparation and execution of intended movements but also for suppressing movements that activate the motor system but are not to be performed.

Moreover, studies of SMA during action observation indicate that it can be considered to be a part of the mirror neuron system (Rizzolatti and Craighero 2004), and is thus related to both motor execution and action observation.

In different studies, many other areas have been implicated in motor imagery, such as prefrontal and subcortical structures (Gerardin et al. 2000), the dorsolateral prefrontal cortex, and the inferior frontal and middle temporal gyri (Stephan et al. 1995). In particular, parietal motor-related cortical areas such as the inferior and the superior parietal lobuli are implicated in motor imagery. Both parietal areas showed activation during motor imagery, with increasing activity related to increased spatial task demands (Wolbers et al. 2003). Parietal stimulation in neurosurgical patients appeared to trigger an intention to move the contralateral limbs or face, and sometimes induced the illusion that a movement had actually taken place (Desmurget et al. 2009). In another study (Sirigu et al. 1996), patients with parietal lesions were found to be impaired at predicting, through mental imagery, the time necessary to perform differentiated finger movements and visually guided pointing gestures. The authors concluded that the parietal lobes are important for the ability to generate mental movement representations.

Thus, both visual mental imagery and motor imagery have been postulated to draw on similar neural resources as the corresponding "actual" abilities (respectively, visual perception and motor acts). However, the available evidence indicates that such a close correspondence only exists for motor imagery. This possibility seems consistent with the proposed "active" character of imagery abilities, which would not necessarily require the functioning of sensory cortices devoted to the processing of external stimuli. The more endogenous levels of processing related to visual mental imagery may instead depend on high-level visual abilities, including the motor-exploratory abilities required by "active vision" processes (Findlay and Gilchrist 2003). For motor imagery, the relationship with actual motor programs would instead be more direct, because only the very last step of the program, i.e., motor execution, would differentiate motor imagery from motor activity.

13.3.1 Clinical Aspects

13.3.1.1 Locked-In Syndrome and Vegetative State

Locked-in syndrome (LIS) defines the condition of patients with a complete disconnection of descending motor pathways, after a lesion of the ventral pons. As a consequence, they show paralysis of all voluntary movements except blinking and eye movements, with preserved consciousness and, not infrequently, spared somatosensory perception (Patterson and Grabois 1986).

Facilitation of motor cortical potentials during imagined movements of paralyzed limbs in a LIS patient was demonstrated by using transcranial magnetic stimulation (Cincotta et al. 1999), thus suggesting the preservation of motor imagery abilities in this patient.

In a recent study, patients with LIS were asked to decide whether two pictures represented the same two (left or right) hands, or two different hands (Conson et al. 2008). Normal subjects answer this type of task by mentally simulating their own body part movements (Parsons 1987a, b). LIS patients with lesions of the ventral pons a demonstrated a dissociation of performance between a disrupted mental manipulation of hands and spared visuospatial object imagery (Conson et al. 2008). This neuropsychological dissociation supports the hypothesis that a lesion of the motor system has a specific negative effect on mental representation of movements of one's own body parts.

The so-called persistent vegetative state is different from LIS and defined as a condition in which the patient is awake but not aware. Recent fMRI evidence obtained in a 23-year-old patient, fulfilling the criteria for a diagnosis of vegetative state (Owen et al. 2006), suggested preserved motor imagery abilities. The patient was given spoken instructions to perform two mental imagery tasks. When she was asked to imagine playing tennis, there was increased BOLD response in the SMA. In contrast, when she was asked to imagine walking through her home, significant activity was observed in the parahippocampal gyrus, the posterior parietal cortex, and the lateral premotor cortex. Her neural responses were indistinguishable from those observed in healthy volunteers performing the same imagery tasks in the scanner. These results are important in suggesting some form of preserved consciousness in some of these patients, who often receive a wrong diagnosis of persistent vegetative state.

13.3.1.2 Vascular Stroke

Due to the shared anatomy involved in motor imagery and motor execution, vascular lesions of these neural networks should lead to a deficit in both processes. Indeed, several studies have demonstrated an impairment of motor imagery after a stroke incident, such as equivalent slowing of real and imagined movements (Gonzalez et al. 2005; Malouin et al. 2004; Sabate et al. 2007). Both patients with severe hemiparesis and healthy controls displayed primarily contralateral activation during an

fMRI experiment, but only the patients showed cortical motor activation also in the hemisphere ipsilateral to the brain lesion, especially in M1 and SMA (Kimberley et al. 2006). This seems particularly frequent in the very early stages of rehabilitation and suggests a tentative compensation from the undamaged brain areas (Calautti et al. 2001; Lacourse et al. 2004). However, there are inconsistencies between the behavioral patterns showed by right- versus left-brain damaged patients, presumably because of variable intrahemispheric location of strokes (Cicinelli et al. 2006; Stinear et al. 2007). Few studies have investigated the involvement of other structures, such as the basal ganglia and the cerebellum. In particular, patients with a putaminal lesion revealed a deficit for motor imagery but not for visual imagery. After a cerebellar stroke, reduced excitability of motor areas was observed as well as a decrease in motor-evoked potentials during motor imagery tasks (Battaglia et al. 2006; Gonzalez et al. 2005).

13.3.1.3   Parkinson's Disease

Patients suffering from Parkinson's disease display phenomena of under- or over-activation in different regions of SMA during mental imagery tasks (Sabatini et al. 2000; Thobois et al. 2000). When these patients performed a motor imagery task with the akinetic hand, positron emission tomography showed decreased activation of the contralateral primary sensorimotor cortex and the cerebellum and more persistent activation of the SMA compared to controls (Thobois et al. 2000). This activity might serve to compensate for akinesia by recruiting other areas involved in motor imagery.

13.3.1.4   Amputees

Patients with limb amputation often suffer from illusory phenomena implicating sensation and movement from the amputated limb (phantom limb). Raffin et al. (2012) asked 19 upper-limb amputees to execute movements of their phantom limbs (the movement was mimicked simultaneously with the intact limb) or to purely imagine them. Patients reported differences in the speed of executed voluntary and purely imagined movements of the phantom, with imagined movements occurring faster. In addition, stump muscle motor activations were always present with voluntary movements, but never with imagined movements.

Even in this group of patients, cortical reorganization plays an important role in motor imagery. Patients with traumatic amputations and associated phantom limb pain show greater reorganization of somatosensory cortex, with invasion of the "amputated" regions by surrounding regions of the sensory homunculus. The experience of pain seems to modulate the internal cortical representation of a limb, and thus the extent of cortical reorganization (Acerra and Moseley 2005; Lotze et al. 2001).

13.4 Conclusions

Mental imagery abilities draw on peculiar sorts of conscious processes (Sartre 1936). A crucial difference between mental images and their "real" counterparts is that mental images are based on active processes of reflective consciousness, as opposed to the more immediate character of perception or movement. As a consequence, imagery abilities make us ontologically free from the constraints of reality (Sartre 1940), as well as from its influence on elementary sensory processing (Mesulam 1998). In this sense, mental imagery is a central feature of our being human.

The endogenous, active character of mental imagery is perfectly consistent with the evidence reviewed above, concerning the neural correlates of its different aspects. Visual mental imagery does not seem to need elementary sensory processing; instead, it draws upon higher level stages of processing, including those concerned with active exploration. In contrast, motor imagery draws upon similar resources as real motor acts, which have to be eventually inhibited.

Neuroimaging studies in normal participants and behavioral and neuroimaging evidence in brain-damaged patients have accumulated an extensive database of knowledge on the brain bases of mental imagery. Thanks to this knowledge, there is now the exciting possibility of exploiting brain patterns of activity in order to explore conscious processing of information in patients with severe impairments of consciousness and communicative abilities. Thus, the study of mental imagery, far from being an abstract field of research in cognitive neuroscience, may ultimately translate to substantial medical advances at the patient's bedside.

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Chapter 14
Imagery Questionnaires: Vividness and Beyond

Simon Lacey and Rebecca Lawson

Abstract Most imagery questionnaires require ratings of the vividness of mental images. But vividness is only weakly related to theoretical models of imagery. In this chapter we review the usefulness of vividness ratings as an index of imagery ability. We contrast this with recent questionnaires that attempt to measure different components of imagery ability in terms of the underlying processes such as image generation, maintenance, inspection, and transformation or in terms of object versus spatial versus verbal cognitive processing styles. We show how these more theory-driven approaches can lead to new insights and argue that such approaches can and should be extended to mental imagery beyond the visual domain.

14.1   Introduction

When Francis Galton, an early exponent of experimental psychology, decided to conduct research into mental imagery, he did so using a questionnaire (Galton 1880, 1907). Questionnaires have remained a staple of imagery research, despite the rise of various neuroimaging methods and their increasing ability to lay bare imagery's essentially private nature (see Chap. 15). Galton's so-called breakfast-table questionnaire (reproduced in Table 1 of Burbridge 1994) anticipates a surprising number

S. Lacey (✉)
Department of Neurology, Emory University School of Medicine,
WMB 6000, 101 Woodruff Circle, Atlanta, GA 30322, USA
e-mail: slacey@emory.edu

R. Lawson
School of Psychology, University of Liverpool, Liverpool, UK

of the topics that would form the backbone of imagery research when it was resumed almost a century later. Some questions clearly concern the vividness of visual imagery, for example, "*Are the colors of the china […] or whatever may have been on the table quite distinct and natural*?" Other items reflect imagery processes, for example, maintenance ("*Can you deliberately seat the image of a well-known person in a chair and retain it, and see it with enough distinctness to enable you to sketch it leisurely*?") or transformation ("*Can you judge with precision of the effect that would be produced upon the appearance of a room by changing the position of the furniture in it*?"). Some items even concern what modern imagery researchers would recognize as the capacity of a visual buffer (Kosslyn 1980, 1994), for instance, "*Extent of field of view—does it correspond in breadth and height to the real field of view*?" and "*How much of a [printed] page can you mentally see and retain steadily in view*?" Other items tackled auditory imagery of voices and music, olfactory and gustatory imagery, and the vividness of imagined smells or tastes relative to visual images of the related object. Thus, the Galton questionnaire reflects many of the themes of later research: the nature of the conscious experience of imagery, the non-unitary nature of imagery and its different components and processes, and the extension of mental imagery beyond vision to other senses and to interactions between imagery in different senses.

Questionnaires are generally used to assess individual differences. Such differences may be theoretically important in that they may reveal separate cognitive systems or strategies that would be masked if all data was pooled (Cornoldi and Vecchi 2003; see also Sect. 14.4 for an example in which reanalyzing data in the light of individual differences led to new information about multisensory representations). Questionnaires may also be important for screening from an applied perspective. For example, the benefit of imagery-based therapies and rehabilitation strategies may be related to individual differences in imagery preferences and abilities. Despite the rise of neuroimaging research into imagery, questionnaires look set to survive as a useful, complementary technique.

In this chapter, we review the usefulness of imagery vividness which has historically been used as an important index of imagery ability. We then go on to discuss how a more process-oriented approach, grounded in a theoretical model, has been fruitful in visual imagery and how this might be translated to other modalities. We also describe how object and spatial dimensions of visual imagery (Kozhevnikov et al. 2002; Kozhevnikov et al. 2005) have been extended into the haptic and multisensory domains, using a theory-driven questionnaire. Finally, we review imagery questionnaires that assess imagery in a number of different modalities.

14.2   Vividness of Imagery

As we shall see in the following section, vividness is not necessarily the most important or informative aspect of imagery. However, it is the most intuitively open to introspection, and many early questionnaires operated on the assumption that

vividness reflected imagery ability (e.g., Betts 1909). This assumption has persisted so that even today the most commonly used imagery questionnaires require people to generate a mental image and to rate its vividness. These include questionnaires assessing a single imagery modality: visual (Marks 1973: Vividness of Visual Imagery Questionnaire [VVIQ]; Marks 1995: Vividness of Visual Imagery Questionnaire-Revised [VVIQ-R or VVIQ-2]), olfactory (Gilbert et al. 1998: Vividness of Olfactory Imagery [VOIQ]), auditory (Willander and Baraldi 2010: Clarity of Auditory Imagery Scale [CAIS]), and those measuring imagery of movement (Roberts et al. 2008: Revised Vividness of Movement Imagery Questionnaire [VMIQ-2]; Campos et al. 1998: Vividness of Haptic Movement Imagery Questionnaire [VHMIQ]). We are not aware of any modality-specific questionnaires that assess vividness for tactile imagery of passive touch that is unrelated to movement, nor for haptic imagery of active touch, or for gustatory imagery. However, these senses are addressed in some multimodal questionnaires in which individuals rate their imagery in a number of senses (e.g., Betts 1909; Sheehan 1967; Switras 1978; Schifferstein 2009: see Sect. 14.5). Note that the VHMIQ (Campos et al. 1998) rates imagery of skin and muscle sensations associated with movement in terms of exertion, temperature, pressure, etc., for example the feel of water moving over the body whilst swimming. It therefore assesses certain aspects of tactile imagery, as it refers to imagined experiences of passive touch. However, it does not require imagery ratings for purposive (Gibson 1966) or active exploratory touch for the purpose of obtaining information about objects (Lederman and Klatzky 1987) which is how haptics is usually defined.

Vividness is an aspect of our conscious experience of imagery (Dean and Morris 2003) which is not necessarily related to the specific content of the image and might therefore be regarded as a surface property of an image. Most questionnaires equate vividness to the similarity between imagery and perception, i.e., to the realism of the image: visual vividness is "a combination of clarity and liveliness […] the more vivid an image […] the closer it approximates an actual percept" (Marks 1972, p. 83). This definition is evoked in the vividness rating scales used in other modalities: "perfectly realistic and as vivid as the actual odor" (Gilbert et al. 1998: VOIQ), "as intense as executing the action" (Malouin et al. 2007: Kinesthetic and Visual Imagery Questionnaire [KVIQ]), and "perfectly clear and as vivid as the real situation" (Campos et al. 1998: VHMIQ). For auditory imagery, however, Willander and Baraldi (2010) distinguish vividness (clarity and liveliness) from clarity (brightness and sharpness). Their CAIS rating scale for vividness asks "subjectively, how clearly do you hear the sounds" with no reference to realism and no comparison to auditory perception. Nevertheless, CAIS auditory clarity ratings were correlated with VVIQ-2 visual vividness ratings (Campos and Pérez-Fabello 2011), suggesting that they might measure the same construct, i.e., the realism of the image.

Questionnaires rely on self-report and may be subject to confounding factors such as socially desirable responding (see Allbutt et al. 2011, regarding the VVIQ). However, Cui et al. (2007) suggested that vividness could be objectively measured. They employed a task in which participants were required to name color words presented against a background that was either congruent or incongruent in color

with the words. Performance on this task correlated with VVIQ scores: highly vivid imagers were less affected by incongruently colored backgrounds. This reverse Stroop effect could be explained if color naming induced color imagery for the vivid imagers, resulting in the color words being easier to see against incongruently colored backgrounds (Cui et al. 2007). Crucially, VVIQ scores strongly predicted both performance on the color naming task and activity in early visual cortex during functional magnetic resonance imaging (fMRI) of a visual imagery task (Cui et al. 2007). Thus, "private" imagery vividness could be read off from the blood-oxygen-level-dependent signal detected in fMRI.

Relationships between vividness ratings and cortical activity have also been found for other modalities. Modality-specific ratings for visual, tactile, gustatory, kinesthetic, and somatic imagery (as measured by the relevant subscales of the Questionnaire Upon Mental Imagery (QMI) Betts 1909) were correlated with activity in modality-specific cortical regions during visual, tactile, gustatory, kinesthetic, and somatic imagery, respectively (Palmiero et al. 2009; Olivetti Belardinelli et al. 2009). In these studies, vividness ratings related to imagery in the same modality: an interesting question is whether vividness ratings in one modality can predict performance or neural activity in another. Kilgour and Lederman (2002) found no correlation between VVIQ scores and performance on a haptic face recognition task. However, Zhang et al. (2004) asked participants to rate the vividness of their visual imagery specifically during the haptic shape perception task in their study (VI_HS) in addition to completing the VVIQ. While VVIQ and VI_HS ratings were not significantly correlated with haptic shape-selective activity in the lateral occipital complex (LOC) when treated separately, when taken together in a multiple regression they strongly predicted haptic shape-selective activity in the right LOC (Zhang et al. 2004). This suggests that vividness ratings might have cross-modal predictive value.

14.3   Beyond Vividness to the Processes Involved in Imagery

Some early questionnaires equated vividness with imagery ability (Betts 1909), and many studies still divide participants into "good" and "poor" imagery groups on the basis that more vivid imagery is better imagery (Dean and Morris 2003; McAvinue and Robertson 2007). However, this is problematic because vividness, however defined, is only weakly connected to theoretical models of how imagery might work (Dean and Morris 2003). In addition, using a single measure of vividness implicitly treats imagery as an undifferentiated ability at which individuals are either good or bad. This ignores the fact that conscious experience of imagery is the product of a collection of subprocesses—image generation, maintenance, inspection, and transformation (Kosslyn 1980, 1994)—and that there are object and spatial subtypes of imagery (see Sect. 14.4): individuals might vary widely in their ability on these subprocesses and subtypes. The ability to generate vivid imagery is thus only one ability among many. We should not, though, conclude that vividness is unimportant;

for example, vividness of motor imagery is a key factor in improving performance (Roberts et al. 2008).

VVIQ scores correlate with a variety of tasks (see Marks 1989) but it is unclear why correlations are, or are not, found, and few studies have found correlations between self-reported vividness and performance on those tasks (usually spatial) that are assumed to rely heavily on imagery (Dean and Morris 2003; McAvinue and Robertson 2007). This may be because (1) vividness is functionally unrelated to performance on these tasks; (2) vividness questionnaires typically require rating of relatively familiar items retrieved or constructed from long-term memory whereas the spatial tests thought to correlate with imagery ability involve constructing novel shapes and holding them in short-term memory; and/or (3) vividness questionnaires do not measure theoretically meaningful imagery processes. With regard to (3), it is worth noting that some visual imagery questionnaires that are still in use predate the detailed exposition of the most advanced model of visual imagery (Kosslyn 1980, 1994; Kosslyn et al. 2006), for example, the QMI (Betts 1909; Sheehan 1967) and the Gordon Test of Visual Imagery Control (Gordon 1949). Such questionnaires may not accurately reflect the current state of knowledge.

Dean and Morris (2003) devised a new questionnaire that required participants to generate an image of either a 2D or 3D novel shape and to imagine it as either static or rotating. Participants then rated their imagery on items that were explicitly cast in terms of Kosslyn's model of visual imagery. For example, they rated how easy it was to generate, maintain, and rotate the image; how detailed and clear it was; and whether this changed during maintenance and rotation. These process-related ratings predicted performance on spatial tests that are assumed to rely on imagery whereas VVIQ scores did not. In addition, the process-related ratings and VVIQ scores were uncorrelated (Dean and Morris 2003).

One reason for these findings may be that the VVIQ and the Dean and Morris (2003) questionnaire required imagery from different sources. The VVIQ requires imagery of familiar items recalled or constructed from long-term memory. In contrast, the spatial tests used by Dean and Morris, and in the majority of earlier studies that they reviewed, require participants to imagine novel shapes using short-term memory. Thus ratings in Dean and Morris (2003) questionnaire may have predicted spatial task performance because the source of the image (novel items constructed in short-term memory) was matched.[1] Their questionnaire is important in demonstrating that participants could introspect successfully about structural aspects of their imagery as well as surface properties of the resulting image, such as vividness. However, in order to obtain a complete picture, it will be important to apply Dean and Morris's (2003) questionnaire to tasks that require imagery of familiar items, such as everyday scenes and objects, in order to examine individual differences in imagery processes for items stored in long-term memory (McAvinue and Robertson 2007).

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[1] Dean and Morris (2003) also note that this finding is an interesting challenge to the Kosslyn model which does not predict any effect on imagery due to the source of the imaged item.

Thus, if we want to know how imagery relates to performance, we should not rely on measuring vividness alone. Instead we must determine what imagery sub-processes are relevant to the task and be aware that the source of the image may be important. An important avenue for future research will be to take this process-oriented approach and to apply it to imagery in other modalities. One barrier to this is that other modalities have less well-developed, or perhaps no, model of imagery. A starting point might be to take what we know of the detailed processes of visual imagery and to see how far these apply to other modalities. This approach raises the problem of whether visual processes can be ported unchanged into other models. For example, whereas generating auditory and visual images might be regarded as similar processes, maintaining an auditory image may be very different to maintaining a visual image given that auditory images (such as imagining a melody) unfold over time anyway.

The Bucknell Auditory Imagery Control Scale (BAIS: unpublished but employed by Zatorre et al. 2010) highlights the difficulties in defining imagery processes across modalities and the importance of definitions for process-oriented questionnaires. The BAIS includes a subscale that rates control of auditory images. This asks participants to rate how easily they can change an auditory image, for example, imagining the sound of a dentist's drill and then the drill stopping and hearing the voice of the receptionist. Here, the concept of control is not clear in terms of imagery processes. Control does not equate solely to maintenance since the image has to be changed, and nor does it appear to equate to image transformation since the task can be accomplished by simply switching to a different image. Similarly, transformation of a visual image is normally a transformation in space whereas for an auditory image it would be a frequency or temporal transformation (for example, (Zatorre et al. 2010) required the temporal reversal of imagined melodies). It is unclear whether these differences are important. Note, though, that for the melody reversal condition the BAIS scores were correlated with activity in the intraparietal sulcus. This area is known to be involved with spatial transformations (Alivisatos and Petrides 1997) and so may be involved in transformations more generally.

14.4   Object and Spatial Imagery Dimensions in Vision and Touch

A recent example of the more theory-driven use of questionnaires advocated in Sect. 14.3 is the investigation of individual imagery preferences using the Object-Spatial Imagery Questionnaire (OSIQ: Blajenkova et al. 2006). A later version incorporates a verbalizer subscale (the Object-Spatial Imagery and Verbal Questionnaire, OSIVQ: Blazhenkova and Kozhevnikov 2009). A detailed account of visual object and spatial imagery can be found in Chap. 16 (see also Kozhevnikov et al. 2002, 2005). In brief, object imagers tend to create images that are pictorial, vivid, and detailed. Their images integrate the structural property of shape with

information about surface properties, such as color, texture, and brightness. By contrast, spatial imagers tend to prefer images that are more schematic and less focused on surface properties. Their images make salient the spatial relations between component parts of objects and support complex spatial transformations.

The representations underlying visual and haptic object recognition share many features (for example, both are orientation dependent and size dependent and are sensitive to changes in surface properties; see Lacey and Sathian 2011, for a review). This begs the question of whether object and spatial imagery dimensions exist for haptics as well as for vision. This was investigated by Lacey et al. (2011). They devised visual and haptic tasks that required discriminating shape across texture changes and texture across shape changes. The same stimuli were used in both tasks for both modalities. In both visual and haptic tasks, when object imagers focused on surface properties they could discriminate texture equally effectively whether shape changed or not. However, when they focused on the structural property of shape, their performance was disrupted if there was a change in texture, indicating that shape and texture tended to be integrated in object imagery. The reverse was true for spatial imagers who, again regardless of modality, could discriminate shape across texture changes but not texture across shape changes, indicating that spatial imagers tended to abstract away from surface properties. Thus object and spatial imagery dimensions appear to exist in both vision and touch, when each modality is tested alone.

In a second experiment, Lacey et al. (2011) reanalyzed data from an earlier study (Lacey et al. 2010) involving cross-modal discrimination of shape across changes in both texture and orientation. Visuo-haptic cross-modal object recognition is thought to be subserved by an orientation-independent multisensory representation (Lacey et al. 2007; Lacey et al. 2009; but see Newell et al. 2001; Lawson 2009). Inspection of the data revealed two levels of performance: one showed above-chance recognition independent of changes in both orientation and texture; in the other, a change in texture reduced performance to chance whether or not there was also a change in orientation. OSIQ scores obtained from participants recalled from the earlier study showed that these two patterns of performance corresponded to the use of object and spatial imagery (Lacey et al. 2011). Object imagers were impaired by a change in texture but not orientation while spatial imagers were unimpaired by either. Furthermore, imagery preference scores based on the OSIQ correlated with cross-modal performance: a preference for object imagery was associated with worse shape discrimination regardless of orientation (Lacey et al. 2011) and was uncorrelated with within-modal object recognition (Lacey et al. 2007). By contrast, OSIQ-spatial scores were correlated with cross-modal object recognition, whether orientation changed or not, but not with within-modal recognition (although the latter approached significance when orientation changed) (Lacey et al. 2007). Taken together, these studies suggested that construction of multisensory orientation-independent representations was linked to the ability to perform spatial transformations. These might include transformations involved in changes of orientation but also translation between differing frames of reference in vision and touch.

Thus, these studies suggest that object and spatial imagery dimensions extend into the haptic and multisensory domains. However, it is important to note that in Lacey et al. (2011) participants were classified not only by reference to the OSIQ but also by self-report in response to a brief explanation of the difference between object and spatial imagery. These two classifications did not always agree, and, in fact, only self-report predicted performance in both within-modal experiments. There may be several reasons for this. Firstly, the tasks focused on whether people integrated surface properties into their images, but only six of the thirty OSIQ items mention surface properties and only three refer to their being included in an image. Most items relate to the difference between pictorial and schematic images and are thus more about format than content. To address this it will be important to develop a questionnaire with subscales probing different aspects of object and spatial imagery. Secondly, the self-report measure explicitly explained the difference between object and spatial imagery while the OSIQ does not (and like many similar questionnaires was not intended to do so). In addition, of course, the OSIQ is a visual questionnaire being applied to a haptic task on the assumption that the object-spatial dimensions are stable across modalities, i.e., that a visual object imager is also a haptic object imager. This assumption remains to be tested. A benefit of creating haptic and multisensory versions of the OSIQ would be that these could be used to compare early-blind, late-blind, and sighted participants on their object and spatial imaging preferences.

14.5 Multisensory Imagery

To our knowledge, there are no multisensory or cross-modal imagery questionnaires that assess people's ability to create images in more than one modality at the same time (for example, simultaneously imagining the sight and sound of an orchestra or the sight and smell of food) or the ability to create an image in one modality from perceptual input in a different modality (for example, creating a visual image of an object from haptic input), although the VVIQ rating scale has been applied to visual imagery of haptically perceived objects (Zhang et al. 2004; see Sect. 14.2).

There are, however, several questionnaires that address unisensory imagery in more than one modality. The earliest, after Galton, is the QMI (Betts 1909) which assesses vividness of imagery in seven modalities: visual, auditory, cutaneous (generally tactile, passive touch), olfactory, gustatory, kinesthetic, and "miscellaneous and organic" (i.e., bodily sensations such as hunger). The short-form version (Sheehan 1967) corrects a potential bias in the full QMI in that it has five items for each modality whereas the full-length version had unequal items and was heavily weighted in favor of visual imagery.

The Survey of Mental Imagery (SMI: Switras 1975, 1978) also assesses seven imagery modalities: visual, auditory, tactile, olfactory, gustatory, kinesthetic, and somesthetic (i.e., bodily sensations). Images are rated for vividness and controllability. The definition of controllability is confusing. It is first described as the

"ability to produce precisely the target image" (Switras 1978, p. 379). This might also be related to image generation, particularly as Switras considers controllability and vividness as "sequential steps in which an image must first be produced before one can evaluate its vividness" (ibid., p. 380). However, controllability is also considered to be the "ability to manipulate, modify, and prolong an image" (Switras 1975 p. 33, cited in Grebot 2003), thus also encompassing the separate processes of maintenance and transformation. Factor analysis did not distinguish between vividness and controllability; instead it extracted factors that reflected single modalities, except for kinesthetic-tactile vividness and controllability factors (Switras 1978). In a shortened version of the SMI testing only four modalities (visual, auditory, somesthetic, and kinesthetic), Grebot (2003) identified separate vividness and controllability factors together with a third, image formation, factor. However, this still leaves several imagery processes confounded under the single heading of controllability.

A different approach was taken by Schifferstein (2009) in a questionnaire assessing five imagery modalities: visual, auditory, tactile, olfactory, and gustatory. Previous questionnaires had specified what images people were to produce, but these might contain cross-sensory confounds. For example, imagining the smell of a rose might also bring to mind a visual image of the color and shape. In Schifferstein's questionnaire, participants are instructed to think of a product or an event that involves a characteristic or conspicuous smell, taste, and so on. It is not clear that this approach completely avoids cross-sensory confounds since, for example, Intons-Peterson (1983) reported that auditory imagery was almost always accompanied by involuntary visual imagery. Nevertheless, Schifferstein's approach does allow participants to think of a personally salient item rather than a forced choice. In addition to vividness ratings, participants rate how well they can imagine, say, a smell; how difficult it was to imagine it; and how strongly they felt that they could really smell it. It is, though, unlikely that these are independent aspects of imagery. How well one can imagine something is related to how difficult it is to imagine, whilst how close the imagery experience is to reality is what vividness is supposed to measure. Indeed all four ratings were highly correlated, and principal components analysis revealed a single factor such that the average of the four ratings was used as the index of image quality (Schifferstein 2009).

Results from all of the above questionnaires rank imagery vividness or quality being greatest for visual imagery and poorest for olfactory and gustatory imagery. But, as discussed in Sect. 14.3, vividness does not appear to provide a good index of imagery ability or reflect the individual contributions of the underlying imagery processes. In addition, concepts such as controllability (Switras 1978) and image quality (Schifferstein 2009) are not well defined. Thus, it is difficult to draw conclusions from these instruments about individual differences in imagery between different modalities or the relative contribution of different processes within a modality. For example, relative to a visual image an olfactory image may be harder to generate and maintain, but we lack theoretically motivated questionnaires that allow such a claim to be tested or that permit individual differences in imagery across different modalities to be measured.

14.6   Conclusions

In this chapter, we have reviewed the usefulness of imagery vividness (i.e., the similarity of imagery to perception) as a source of information about imagery processes and individual differences in imagery ability. We conclude that the strong emphasis on measuring vividness in many imagery questionnaires is not warranted given the relatively weak evidence that vividness predicts imagery performance. We argue that there is a pressing need for theoretically driven questionnaires that address clearly defined component processes of the imagery system in each modality (e.g., Dean and Morris 2003). Visual imagery may be a convenient starting point for this endeavor but we need to be wary of assuming that imagery processes are the same across modalities. At issue is whether it is appropriate to develop process-oriented questionnaires for nonvisual modalities based on our understanding of visual imagery or whether more open-ended theoretical research into imagery within each nonvisual modality is required before appropriate questionnaires can be developed. The reality is probably that, in order to understand the relationship between imagery systems in different modalities, and individual differences therein, both approaches will be required to work in tandem to make progress.

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Chapter 15
Cognitive Neuroscience of Mental Imagery: Methods and Paradigms

Giorgio Ganis and Haline E. Schendan

Abstract Over the last three decades, several new conceptual and experimental methods and paradigms have become available to cognitive scientists and neuroscientists to investigate mental imagery experimentally. This chapter critically reviews the strength and weaknesses of four classes of these methods and paradigm: behavioral, neuroimaging, electrophysiological, and brain stimulation. Behavioral paradigms provide researchers with powerful tools to explore and document mental imagery phenomena, but usually they cannot unambiguously determine the underlying neural processes. Neuroimaging and electrophysiological paradigms are often based on behavioral ones and complement them because they provide additional information about the brain mechanisms recruited by mental imagery that can be used to constrain theories. Finally, brain stimulation paradigms further complement the behavioral and neuroimaging methods by providing information about the causal role of postulated neural mechanisms in mental imagery. Systematic use of these kinds of methods and paradigms will dramatically increase our knowledge of mental imagery and enhance the sophistication of our theories, fostering a healthy scientific discovery cycle.

G. Ganis (✉)
School of Psychology, Cognition Institute, University of Plymouth,
Drake Circus, Plymouth, Devon, PL4 8AA, UK

Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital,
Charlestown, MA 02129, USA

Department of Radiology, Harvard Medical School, Boston, MA 02115, USA
e-mail: ganis@nmr.mgh.harvard.edu

H.E. Schendan
School of Psychology, Cognition Institute, University of Plymouth,
Drake Circus, Plymouth, Devon PL4 8AA, UK

Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital,
Charlestown, MA 02129, USA

15.1 Introduction

Mental imagery is an omnipresent phenomenon in our cognitive life. The key problem of studying mental imagery scientifically is that imagery is a subjective phenomenon and cannot be observed directly by the experimenter. This characteristic of mental imagery explains to a large extent classic and rather fruitless debates such as the one on the existence of imageless thought at the beginning of the twentieth century, which relied purely on introspective methods (reviewed in Kroker 2003). Substantial progress in the scientific study of mental imagery became possible only after the 1960s, with the introduction of more objective behavioral and cognitive neuroscience methods and paradigms, and these are the focus of this chapter (Kosslyn et al. 2006). Combining behavioral and neuroscience methods enabled researchers to begin addressing experimentally questions about mental imagery that would have been impossible to answer using behavioral methods alone (e.g., Anderson 1978).

15.2 Behavioral Methods and Paradigms

Although mental imagery is a subjective experience, researchers can attempt to make inferences about its inner workings by using indirect measures theorized to be affected by imagery in a predictable manner. This general logic is not different from that used in many scientific disciplines in which the entities of interest cannot be observed directly (e.g., planetary astrophysics). One class of methods to study mental images experimentally entails asking people questions about properties of their own mental images and by measuring the pattern of responses as one would do for responses about percepts of real objects. Thus, for instance, to probe auditory mental imagery researchers can ask someone to image a certain well-known tune (e.g., the Pink Panther theme) and to compare the pitch of pairs of notes within it (e.g., Halpern 2001). Or they can ask someone to image a pair of common objects (e.g., a cat purring and bird chirping) and decide which one usually produces a higher pitch or a lower pitch (e.g., Intons-Peterson et al. 1992). A correct answer suggests that the accuracy of the generated mental image is sufficient to support this kind of judgment, whereas an incorrect answer suggests otherwise. Furthermore, the pattern of response times (for instance, slower response times when the pitches to be compared are more similar to each other) provides information useful to infer the internal organization of mental images. Likewise, in the seminal work on mental rotation, increases in response times as a pair of objects are rotated relative to each other have been taken as support for the idea that people

rotate objects mentally as they can do with objects physically, with larger rotations taking more time (Shepard and Metzler 1971). Similarly, during visual mental imagery, the task could be to visualize capital letters of the alphabet or common objects and to decide whether they have certain visual attributes (e.g., curved or straight lines) (Ganis et al. 2004; Kosslyn et al. 1995). Again, if mental image representations are organized like perceptual representations, there should be similar patterns of response times and accuracy in the two cases.

One potential problem with this logic is that it assumes that the task can be carried out only using mental imagery, which is not necessarily the case. For example, in the case of a tune, if someone plays the piano, and the tune is very familiar to this person, it is possible that one could use kinesthetic/motor representations about their fingers on the keyboard (Neuper et al. 2005), which could include tactile/motor imagery, rather than auditory imagery. Analogously, answering questions about letters may be possible by using motor representations stored in memory when learning motor plans to execute such letters (Ganis et al. 2003). These examples illustrate that the type of mental imagery required for the task (e.g., motor imagery) may not be the type targeted by the experiment (e.g., auditory imagery). In other cases, and perhaps more insidiously, the answers to the probed judgments may have been already encoded in semantic or episodic memory. Consequently, one might simply retrieve the answer (e.g., "grass is green" in response to questions concerning the color of grass) without resorting to mental imagery at all to answer the question.

These potential problems are especially troublesome for interpreting mental imagery results when researchers try to determine whether or not a certain brain region is critical for imagery by studying neurological patients or using the brain stimulation methods summarized later: Some patients may show good performance in an imagery task simply because they resort to other strategies that do not involve imagery in the target modality to solve the task (Ganis et al. 2003). Thus, the choice of stimuli and attributes to be judged must be made very carefully in order to draw meaningful conclusions. To minimize this problem, studies should focus on mental imagery of items or events learned just before the test of mental imagery. They should also use judgments that are unlikely to be employed to encode the stimuli at study and that require the generation and inspection of a mental image during the test to be performed successfully.

An important extension of these paradigms employs perceptual information to probe imagery. Using visual imagery as an example, people may be asked to image a familiar visual stimulus and then to decide whether a small visual probe falls on or off the visualized stimulus or whether certain features of the visual mental image are in register with the perceptual probe. In a classic example of such a paradigm, participants were asked to visualize a capital letter within a rectangular grid and then to decide whether a probe fell on a grid cell that was covered by the visualized letter (Podgorny and Shepard 1978). In a related example, participants visualized capital letters within a "Mercedes" symbol and decided which one of the 2 sectors of the symbol contained more area of the visualized letter (Ganis et al. 2005). Another example is the "clock task," in which participants are asked to visualize the hands of an analog clock by using a numeric probe (e.g., 8:15 p.m.) and to decide if

a subsequently presented dot falls in the smallest disk sector delimited by the hour and minute hands (Cattaneo et al. 2011).

Although these paradigms enable the study of mental images using psychophysical methods and provide a way to ensure that participants perform the mental imagery task, they may also introduce spurious perceptual and attentional processes to the task. For example, if performance on the dot task is poor, that may not be due to the attributes or precision of the visual mental images per se, but to some complex interaction between imagery and these other perceptual and attentional processes. Thus, poor performance could be due to a problem with integrating the visual mental image and the perceptual probe required to perform the task or to maintain a visual mental image in the presence of a perceptual stimulus.

One effective way to deal with this issue is to turn the problem on its head and to exploit potential interference patterns between imagery and perception to attempt to make inferences about the attributes of mental images. In a classic study using this logic, participants were asked to generate visual or auditory images while at the same time detecting faint visual or auditory stimuli (Segal and Fusella 1970). The similarity between mental images and percepts within the same modality was inferred from the resulting pattern of interference. In a refinement of this type of paradigm, participants were asked to form visual mental images of a Gabor patch, and the effect of imagery was assessed on detection rates of flanking Gabor patches (Ishai and Sagi 1995). By varying parameters such as the orientation and position of the flanking Gabor patches, relative to those of the visualized patch, it was possible to infer some of the characteristics of the generated visual mental images. For instance, detection thresholds were lower when the orientation of the imagined and perceived Gabor patches was the same, suggesting the involvement of neural representations sensitive to orientation of the kind found in early visual cortex.

Another method to deal with the problem of overlap between imagery and perception processes during the task is to uncouple these two processes in time by examining the effects of imagery on subsequent perception. A recent example using this logic employed the phenomenon of binocular rivalry, in which two incompatible stimuli are presented to the two eyes and constantly compete for perceptual dominance (Pearson et al. 2008). On each trial, participants were asked to visualize a vertical or a horizontal grating, and the effect of imagery was assessed on the bias produced on a subsequent binocular rivalry period using those two stimuli. Again, by varying the parameters of orientation and position of the binocular stimuli, it was possible to infer details about the mental image representations, including that these representations are not the same ones used during visual attention and that they are functionally similar to perceptual representations in early visual areas (Pearson et al. 2008). Adaptation paradigms that explore perceptual adaptation effects induced by mental imagery also fall within this class. In these paradigms, typically participants image a stimulus, and the resulting adaptation effects on subsequent perceptual stimuli are examined (e.g., Dils and Boroditsky 2010; Mohr et al. 2011; Mohr et al. 2009; Seurinck et al. 2011; Winawer et al. 2010). For example imagining a vertical grating affects the perceived orientation of a subsequent, near-vertical

grating (Mohr et al. 2011), and the exact amount of distortion can be measured psychophysically.

Despite the power and range of behavioral methods used to investigate mental imagery, it is typically difficult to pinpoint the exact locus of behavioral effects because such effects are the endpoint of a cumulative chain of events unfolding in our brain. The neuroscience-based methods described next attempt to determine the locus of such effects more precisely by investigating their brain basis.

15.3   Neuroimaging Methods and Paradigms

A complementary set of methods and paradigms to investigate mental imagery relies on examining its neural correlates by means of neuroimaging techniques. This approach is relatively recent as it became possible only with the advent of the noninvasive tools of cognitive neuroscience (Ganis and Kosslyn 2002). The behavioral paradigms to study mental imagery using neuroimaging technologies are often drawn from the existing behavioral literature, but they usually need to be modified because of the constraints imposed by each neuroimaging technique. In this section, we focus on the functional magnetic resonance imaging (fMRI) technique because it is the most widely used neuroimaging methodology and because the seminal studies on mental imagery carried out using positron emission tomography are already summarized in Chap. 4. For fMRI, behavioral paradigms need to be adjusted to accommodate the continuous loud noises produced during standard fMRI scanning protocols. This requires clever methods and designs to avoid interference during auditory perception and imagery studies, such as sparse temporal acquisition schemes or clustered-sparse temporal acquisition designs (Schmidt et al. 2008; Zaehle et al. 2007). Furthermore, the timing of stimulus presentation needs to be calibrated so as to accommodate the temporal constraints of event-related or blocked designs (e.g., Dale 1999). Note that even though the methods described in this section have been used mainly in visual mental imagery studies, they are sufficiently general that they can easily be adapted to study other imagery modalities as well (e.g., auditory, olfactory, motor).

Most neuroimaging studies of mental imagery have used univariate analysis methods aimed at (1) revealing the neural signature of mental imagery content; for example: Is the average neural activation in a given region of interest systematically different when people visualize a dog or a cat? and (2) comparing mental imagery and perception conditions in the same modality to determine the extent to which average brain activation in a given region of interest overlaps in the two cases. For example, in one of the few fMRI studies that compared the pattern of similarity between mental imagery and perception across the entire brain, participants first memorized a set of stylized pictures of common objects. Next, they saw or imagined these stimuli (half of the pictures were used for the imagery task and the other half for the perception task, counterbalanced across participants) after hearing their name (Ganis et al. 2004). For both conditions, the task involved judging attributes

of previously studied objects such as whether the top right part of the object was higher than the top left, to ensure that participants generated precise and vivid mental images. The analyses involved comparing each condition to its own baseline, which in this case was the idle time between successive trials during which no stimuli were presented, and then comparing the resulting patterns of brain activation in the two conditions with each other. Similarity metrics can then be used, either across the entire brain or within given regions of interest. For example, one could simply count the proportion of voxels activated in common between mental imagery and perception or carry out conjunction analyses (Ganis et al. 2004; O'Craven and Kanwisher 2000).

However, overlap analyses of this type may ignore subtle details of the spatial pattern of neural activation because results are now binary: Voxels are either active or not. Spatial details are further lost to the extent that spatial averaging within a region of interest is carried out. Multivoxel pattern analysis (MVPA) methods attempt to address this issue by providing more sensitive measures of spatial similarity that can yield additional information on whether two conditions engage the same neural populations (e.g., Tong and Pratte 2012). MVPA assume that perceptual and cognitive processes are carried out in a distributed manner in the brain and so they examine and compare the distribution of brain activation across many voxels (Haxby et al. 2001). Since these methods have received much attention recently (e.g., Tong and Pratte 2012), they are described in greater detail, and some examples of the way they have been employed to study mental imagery are summarized next.

Like univariate analyses, MVPA can address two key questions that are relevant for the study of mental imagery. First, are certain spatial patterns of brain activation elicited during mental imagery consistently associated with the content and modality of the mental images? Second, are these spatial patterns similar to those observed during perception of the corresponding content and modality? In one fMRI study using MVPA, participants either perceived two letters ("O" or "X") or visualized them following an auditory cue, in different blocks of trials (Stokes et al. 2009). For the logic to work, multiple scans are required, each containing one block for each type of trials in order to be able to assess generalization. In this study, six scans were used, with each scan containing one block of perception and one block of mental imagery trials. To address the first question (imagery content), a linear classifier was trained to discriminate brain activation elicited by the letter "O" from that elicited by the letter "X," independently for imagery and perception, using a subset of the data (training dataset-usually 75% or more of the data). Following the so-called searchlight procedure (e.g., Haynes et al. 2007; Kriegeskorte et al. 2006), this training step was performed with data from a small sphere (about 100 voxels) that changed location sequentially until the entire brain was probed. Next, for each spatial location of the sphere, generalization was evaluated by determining how well the classifier performed on the test dataset, providing information on the reliability of the discrimination for every probed region for the perception and imagery conditions. In this study, above chance discriminative clusters within perception and imagery were found in high-level visual areas including the lateral occipital

complex (LOC) and the inferior and middle occipital gyrus (Stokes et al. 2009). To address the second question (perception vs. imagery), a linear classifier was trained on the perception dataset and then tested on the corresponding mental imagery data. Above chance classification for imagery was achieved using perception data from the anterior left LOC, suggesting that some of neural populations engaged by mental imagery in these regions (at least at the scale probed by fMRI) are the same as those engaged by perception.

A more recent fMRI study implemented an improved design (Reddy et al. 2010). First, classification was attempted among four categories of objects (common fruits and vegetables, tools, famous faces, famous buildings) instead of just two letters. Second, an additional task was employed in which participants decided whether the color of the object to be visualized on the current trial was the same as for the previous trial. Although this task was unlikely to force participants to carry out high-resolution visual mental imagery, it provided some validation that participants were actually carrying out mental imagery, unlike the previous study. The four object categories were presented visually (i.e., perceived) or just imagined in different blocks. As in the previous study, a subset of the dataset was used to train a classifier (in this case, the classifier was a support vector machine, SVM, which finds the classification surface that maximally discriminates between items belonging to different categories) to discriminate each object category from the others, and generalization was assessed on the remaining portion of the dataset. These analyses were conducted within regions of interest defined by means of independent localizer runs to identify object-responsive regions in occipito-temporal and temporal cortex. Results indicated that the correct test category was predicted at levels above chance using the training dataset from the same modality (67% for perception and 50% for imagery, with chance being 25%). Furthermore, the results generalized across conditions, so that training on the perception data enabled one to predict the correct category in imagery with about 50% accuracy, and the same result was found when the roles of imagery and perception were reversed. The same analyses conducted on early visual cortex (V1 and V2) revealed above-chance accuracy for the perception case (50%), but not for imagery (26%). This result is not entirely surprising, as discussed in Chap. 4, because no task was used to ensure that participants generated high-resolution images of the objects which may be required to recruit V1 and V2 during mental imagery (Kosslyn and Thompson 2003). An interesting methodological advance of this study was the use of a control analysis to ensure that the results were due to the distributed spatial pattern of activation as opposed to mean activation levels. In this analysis, the data from the regions of interest was scrambled so as to preserve the average activation level but disrupting the spatial pattern details. In this control analysis, accuracy rates fell to chance (25%) as should be expected if the spatial pattern, not activation level alone, drove the results.

The next obvious step in this progression of paradigms is to extend these methods to more than four object categories to determine if the paradigm can scale up. A recent fMRI study using the same general MVPA logic did exactly this and tried to determine the extent to which it was possible to predict which one of the ten common objects was perceived or imagined, based on the pattern of brain activity

in occipito-temporal and temporal cortex as well as in area V1 (Lee et al. 2011). An event-related paradigm was used, with interleaved imagery and perception trials, in which the color of a fixation cross indicated the type of the upcoming trial. Participants were told which object to visualize by hearing the corresponding object name at the beginning of each imagery trial. One caveat, however, is that no task was employed to ensure that participants were actually using mental imagery. The same names were also used for the perception trials, to try to equate the two conditions. An SVM was trained on 83% (5 runs out of 6) of the data, and the resulting model was tested on the remaining 17% of the data (remaining run). Classification performance for the perception condition was over 60% correct using information from V1 and extrastriate cortex and over 40% using information from LO and the posterior fusiform gyrus (chance level in this case was 10%). Classification performance during imagery was at chance for V1 data and at most 15% for data from the remaining three regions. Furthermore, cross-decoding between imagery and perception was above chance in all areas, but accuracy was very low (<15%, again, with a chance level of 10%). Although these results suggest that imagery and perception may engage some common neural populations in the studied visual areas, they also show important differences between imagery and perception. Importantly, the near-chance classification results may be due in large part to the lack of an imagery task that required participants to generate high-resolution visual mental images. In addition, a novel and promising analysis method was applied in this study: Multidimensional scaling to the brain data was used to determine whether the representations used during perception and imagery exhibited the same similarity structure. Results suggested that the neural representations engaged by imagery and perception were much more similar in the posterior fusiform gyrus than elsewhere, perhaps not surprisingly, since these regions are less sensitive to low-level visual properties that differ between imagery and perception.

All in all, these and related neuroimaging methods and paradigms not reviewed here have begun to titrate the pattern of similarity found behaviorally between imagery and perception by showing directly and precisely that imagery and perception share representations in some brain areas more than in others. Although this information is very important, it gives us only a partial view of these processes, as neuroimaging methods based on blood-related measures currently lack the temporal resolution required to resolve the moment-to-moment, neural dynamics of activation of these representations, as discussed next.

15.4 Electroencephalographic Methods and Paradigms

Existing neuroimaging techniques have the problem of low temporal resolution because they measure slow hemodynamic consequences of neural activity rather than neural activity itself (Logothetis and Wandell 2004). However, many of the differences between imagery and perception are likely to depend on the precise timing of interactions between brain areas such as the prefrontal and sensory cortices

(Ganis and Kosslyn 2007). The temporal details of dynamic engagement cannot be measured using fMRI, making it difficult to obtain information that can be used to understand how these processes unfold. In contrast, brain-sensing techniques such as electroencephalography (EEG) and magnetoencephalography (MEG) can measure such temporal details because they reflect real-time neural activity (Ganis and Kosslyn 2002). There have been very few mental imagery studies using EEG, in part because meaningful EEG designs are harder to devise and in part because the final results can sometimes be harder to interpret than an fMRI image with discrete foci of activation.

The most straightforward strategy for using EEG to investigate mental imagery entails analyzing the EEG frequency domain. The advantage of this approach is that it provides one solution to the problem of the substantial trial-to-trial latency variability in the generation of a mental image and the requirement of EEG/MEG to have an event with which to time-lock in order to analyze the data. This strategy has often been used to study motor imagery. In an example of a study using this strategy, participants were cued by a visual stimulus to imagine either left- or right-hand movements as their EEG was measured bilaterally from central and parietal sites over motor representations of the two hands. Results showed reduction of EEG power in the alpha and beta bands at recording sites contralateral to the imagined hand and an increase of power in these bands at ipsilateral recording sites. Power at these frequencies could be used to tell whether a participant had imagined a left- or a right-hand movement in single trials with 80% accuracy (Pfurtscheller et al. 1997). More sophisticated methods using wavelets and single-trial analyses make this approach especially promising for studying mental imagery (e.g., Hsu and Sun 2009). However, time resolution is lost with such EEG analysis methods because the frequency spectrum is analyzed within a relatively long time period (e.g., 500 ms), reducing the temporal resolution from the 1 ms during recording to whatever the analysis time period allows (e.g., 500 ms).

The most common way to use EEG to study cognition with high temporal precision is to time-lock the ongoing EEG to the stimuli of interest and average across many trials to yield event-related potentials (ERPs). However, one of the requirements of ERPs is that the processes of interest should have a constant latency relative to a known stimulus. This requirement is relatively easy to meet with perceptual stimuli (e.g., a tone or a picture) because the timing can be controlled precisely. A limited set of mental imagery paradigms meet this requirement, such as mental rotation and mental paper folding, because a perceptual stimulus is presented that initiates the set of processes leading to mental imagery, from perception through response. In the most common mental rotation paradigm used with ERPs, participants see a well-known alphanumeric character at one of several orientations of in-plane rotation from the canonical upright and decide whether each character is in its normal or mirror-reversed version. Results reveal systematic increases in late, slow, and parietal negativity between 400 and 800 ms as orientation away from the upright increases (Heil and Rolke 2002). During the classic Shepard–Metzler mental rotation paradigm, pairs of objects constructed from a number of cubes are presented rotated relative to each other, and subjects judge whether they are identical or mirror

images of each other. Results show that, in addition to rotation effects on parietal negativity an earlier frontal N3 complex, a negativity peaking around 350 ms, is more negative for higher than lower rotations in-plane (Ruchkin et al. 1991) and in-depth (Schendan and Lucia 2009).

However, the requirement to time-lock to a known stimulus is not trivial to satisfy when trying to answer most other questions about the temporal dynamics of mental imagery because there is substantial trial-to-trial latency variability in the generation of a mental image (Ganis and Schendan 2008). If one simply time-locked the EEG to the presentation of a probe (e.g., the name of a letter to visualize), the resulting average ERP likely would be so smeared in time due to latency variability in generating the mental image that it may be a poor and distorted measure of the underlying imagery processes of interest. Note that this is not an issue with the neuroimaging methods described earlier because they measure slower hemodynamic activity that is not as affected by temporal jitter in neural activity on the order of hundreds of milliseconds.

At least two strategies can be used to attempt to deal with this issue. The first strategy is to try to minimize trial-to-trial latency variability by using overlearned elementary stimuli such as gratings or tones that are imagined repeatedly. For example, in a recent study, participants were asked to imagine one of the two elementary visual patterns (either a black and white checkerboard or a colored pattern) multiple times, following the regular rhythm set by an auditory probe (Page et al. 2011). Results suggested systematic differences between mental imagery of the two patterns and showed similarity between the corresponding perceived and visualized patterns. Although this strategy may work with simple and highly practiced stimuli, it is clearly problematic if the question of interest has to do with mental imagery of more complex stimuli stored in long-term memory (e.g., faces of celebrities). Like in other paradigms and methods covered earlier, a second strategy is to assess the effect of imagery on subsequent perceived stimuli with low latency variability, instead of focusing on imagery directly, and then use this information to infer something useful about imagery. In a seminal ERP study, for example, participants were asked to visualize one of the two letters, followed by the presentation of an actual version of the letter, either matching the visualized letter or not (Farah et al. 1988). The effect of imagery was inferred by examining the ERPs to the visually presented letter, eliminating the problem of latency variability during imagery. The effect of imagery on the ERPs began by 200 ms and had an occipito-temporal scalp distribution, thus suggesting an early visual locus. A more recent ERP study using a similar, but improved, strategy determined the effect of numerous imagined faces or objects on subsequently presented pictures of the same set of stimuli (Ganis and Schendan 2008). Results also showed imagery effects before 200 ms, and with a scalp distribution consistent with neural activity in face-selective occipito-temporal regions.

The neuroscience methods discussed so far focus on documenting brain activation that correlates with imagery tasks. However, it is theoretically important to go beyond correlations and to show that such activation is actually necessary to carry out mental imagery, the topic of the next section.

15.5 Brain Stimulation Methods and Paradigms

Neuroimaging methods can monitor neural activity elicited by imagery in exquisite temporal and spatial detail, but they cannot tell us whether such activity is necessary to carry out imagery successfully. Neuromodulation methods are the only ones that enable researchers to directly address issues about the causality of neural activation. Currently, there are two noninvasive neuromodulation techniques that can be used in humans: transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS). Perhaps the main differences between these two methods are the following: (1) tDCS is much less focal than TMS and (2) tDCS is easier to administer than TMS since the equipment required is less expensive and portable. Since tDCS has been used very infrequently to study mental imagery, we will focus on TMS methods.

During TMS, researchers temporarily interfere with neural activity in a target brain region by means of one or more magnetic pulses delivered using a special coil held against the scalp overlaying the target region (Rossini et al. 2010). Different types of TMS protocols vary in the parameters of the stimulation and the type of coil they employ. Single-pulse TMS delivers one pulse at a specific time during processing, causing disruption of neural activity that can last up to 40–60 ms (Amassian et al. 1989; Brasil-Neto et al. 1992), which can be useful to measure the timing of processes very precisely. In contrast, repetitive TMS delivers rapid trains of pulses, which can produce stronger and longer lasting disruption of neural processing (probably due to temporal summation), but result in lower temporal resolution. Repetitive TMS also comes in different flavors depending on the temporal pattern of pulse delivery. During low-frequency TMS, there is at least 1 s between successive pulses. Hybrid methods deliver short trains of pulses (e.g., repeating clusters of 3 pulses spaced 25 ms apart) so as to retain some of the advantages of both single-pulse and repetitive protocols (e.g., Schuhmann et al. 2009).

Few TMS studies have investigated mental imagery, but findings so far support the idea that sensorimotor areas have a causal role. One class of TMS paradigms determines the effects of magnetic stimulation on imagery tasks immediately or soon after TMS delivery. Designs in which the imagery tasks are carried out off-line, after TMS delivery, have the advantage that they are not confounded by nonspecific factors due to discomfort during the TMS session such as the noise generated by the coil or the distraction caused by muscle twitches. These types of "off-line" designs are only possible with TMS protocols that produce changes lasting for some time after stimulation. One such protocol is 1 Hz TMS stimulation (a form of low-frequency repetitive TMS), which is thought to produce a decrease in the excitability of local networks, making it harder for neurons to fire for several minutes after stimulation (e.g., Boroojerdi et al. 2000). The rule of thumb is that the effect will last about half the duration period of the stimulation (Robertson et al. 2003). One study using this logic assessed the effect of 1 Hz stimulation to medial occipital cortex for 10 min on subsequent visual perception and mental imagery tasks (Kosslyn et al. 1999). Participants were asked to carry out objective judg-

ments on attributes of perceived or visualized high-resolution patterns they studied just before performing the tasks, in independent blocks. The site of TMS stimulation was determined by using positron emission tomography data in a different group of people tested on the same visual mental imagery task. In addition to the real TMS stimulation conditions, there was also a sham TMS condition in which the coil was held against the occipital pole but oriented away from the cortex. Results showed that both visual perception and visual imagery tasks were slowed down during real compared to sham TMS, supporting the idea that medial occipital cortex is necessary for both tasks. A similar logic has been employed in auditory imagery studies. In the main condition of one such study (Halpern 2001), participants imagined nonverbal tunes and performed a pitch judgment between the first and the second note in the tune. This same auditory imagery task was used in a previous PET study, which provided information on potential areas to target with TMS. These included the left and right primary and secondary auditory cortex, which were engaged during auditory mental imagery. 1 Hz TMS delivered to the right, but not left, auditory cortex (encompassing both primary and secondary auditory cortex) slowed down performance on the auditory imagery task, relative to a pre-stimulation baseline.

An example of a hybrid TMS protocol used to investigate imagery is provided by a recent study in which trains of 3 TMS pulses spaced 100 ms apart were delivered to early visual cortex during the visual mental imagery generation phase of the clock task summarized earlier (Cattaneo et al. 2011). In this study, TMS was used in combination with an adaptation paradigm. The first phase of the study demonstrated that adaptation of the upper part of the lower hemifield with a perceptual stimulus reduced imagery performance in the corresponding hemifield during the clock task. The second part of the study revealed that this adaptation effect was abolished by TMS to early visual cortex, suggesting that neural populations in early visual cortex are responsible for the adaptation effect during visual mental imagery.

A recently developed TMS repetitive stimulation protocol is theta-burst stimulation (TBS) which involves the continuous delivery of triplets of pulses at 50 Hz with 200 ms between the pulse triplets (Huang et al. 2005). One advantage of this protocol is that with very short application times (e.g., 40 s) one can achieve inhibitory effects that last up to 30 min (Zafar et al. 2008). For instance, a recent study showed that TBS to primary motor cortex can disrupt learning benefits produced by motor imagery, indicating that primary motor cortex is involved in motor imagery and in some of the learning effects associated with it (Debarnot et al. 2011).

A more indirect use of TMS involves employing magnetic pulses to probe the state of the cortex, rather than to disrupt cortical neural activity (e.g., Sparing et al. 2002). For instance, researchers can probe the excitability of the motor cortex (hand area) by delivering a TMS pulse and by determining the motor threshold, that is, the minimum stimulation strength (relative to maximum TMS stimulator output) required to elicit motor-evoked potentials measured from the hand 50% of the time. The effect of imagery (motor or other modality) on motor cortex excitability can then be assessed by measuring changes in motor threshold. Similarly, the effects of visual mental

imagery on early visual cortex excitability can be assessed by measuring phosphene thresholds, that is, the stimulation intensity required to elicit phosphenes 50% of the time (Abrahamyan et al. 2011). In an example of a study using this logic, participants were asked to perform either a visual mental imagery or an auditory imagery task as their phosphene thresholds were measured (Sparing et al. 2002). The results of this study showed increased visual cortex excitability with visual mental imagery.

tDCS is a noninvasive and inexpensive technique that delivers a weak, constant current to a particular location on the head, affecting the underlying brain tissue. tDCS is believed to produce excitability shifts by means of subthreshold neuronal membrane depolarization (Nitsche et al. 2003; Nitsche and Paulus 2000; Priori 2003). Cathodal tDCS (-electrode) can decrease cortical excitability and thus, for instance, may slow down response during a given cognitive task. So far, there have been very few attempts to use tDCS to study mental imagery. In one such study, cathodal tDCS was applied to primary motor cortex for 5 min, demonstrating reduced motor cortex excitability during rest and motor imagery (as assessed by measuring motor-evoked potentials) for up to 30 min after stimulation (Quartarone et al. 2004). This is consistent with a role of primary motor cortex in motor imagery.

The fMRI results showing that commonly activated regions during visual mental imagery and perception can nonetheless show distinct spatial patterns of activity for different conditions highlight one potential complication of drawing inferences from TMS and tDCS. For example, stimulation of a cortical patch showing effects of both imagery and working memory does not necessarily imply that imagery and working memory recruit this piece of cortex in exactly the same manner. Disruption of the same brain regions may lead to performance impairment in two tasks even though these tasks are supported by different neural populations, for example if the two types of neural populations are interdigitated. Thus, inferences about specific processes may be harder to make than it may appear at first sight, and only convergent evidence can provide conclusive answers.

15.6 Conclusions

The methods and paradigms briefly reviewed in this chapter illustrate the broad armamentarium of research tools available to cognitive scientists and cognitive neuroscientists to study mental imagery experimentally. All methods and paradigms reviewed have some advantages and disadvantages that probably can be overcome only by devising new ways to integrate them with each other. Such integration is far from trivial in part because different methods often have different constraints on the type of design they require and in part because they tap into different aspects of mental imagery processes. Purely behavioral methods enable researchers to document important distinctions between different types of mental imagery processes and between mental imagery processes and other cognitive processes such as attention and working memory. Neuroimaging methods provide information about which brain regions may underlie such processes. Neurostimulation methods complement

the neuroimaging ones by telling us whether certain regions are necessary to carry out mental imagery and what components of mental imagery. Electrophysiological methods also complement the insights provided by neuroimaging methods by enabling researchers to examine mental imagery processes that unfold too rapidly to be resolved with hemodynamic-based methods.

Developing new experimental methods is probably only one component of this integration process. Most likely, the other component will require new integrative tools from computational neuroscience and biophysics. This exciting endeavor will require substantial interdisciplinary work.

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Chapter 16
Individual Differences in Object Versus Spatial Imagery: From Neural Correlates to Real-World Applications

Maria Kozhevnikov and Olesya Blazhenkova

Abstract This chapter focuses on individual differences in object and spatial–visual imagery both from theoretical and applied perspectives. While object imagery refers to representations of the literal appearances of individual objects and scenes in terms of their shape, color, and texture, spatial imagery refers to representations of the spatial relations among objects, locations of objects in space, movements of objects and their parts, and other complex spatial transformations. First, we review cognitive neuroscience and psychology research regarding the dissociation between object and spatial–visual imagery. Next, we discuss evidence on how this dissociation extends to individual differences in object and spatial imagery, followed by a discussion showing that individual differences in object and spatial imagery follow different developmental courses. After that we focus on cognitive and educational research that provides ecological validation of the object–spatial distinction in individual differences—in particular, on the relationship of object and spatial–visual abilities to mathematics and science problem solving and then to object–spatial imagery differences between members of different professions. Finally, we discuss applications of the object–spatial dissociation in imagery for applied fields, such as personnel selection, training, and education.

Keywords Visual imagery • Object–spatial dissociation • Individual differences • Visualization abilities • Cognitive neuroscience • Educational applications

M. Kozhevnikov, Ph.D. (✉)
Department of Radiology, Harvard Medical School,
Martinos Center for Biomedical Imaging,
149 Thirteenth Street, Suite 2301, Charlestown, MA 02129, USA

Department of Psychology, National University of Singapore, Singapore
e-mail: mkozhevn@nmr.mgh.harvard.edu

O. Blazhenkova, Ph.D.
Department of Psychology, National University of Singapore,
Singapore, Singapore

16.1   Introduction

This chapter focuses on individual differences in object and spatial–visual imagery both from theoretical and applied perspectives. The research reviewed here is based on a new approach to examining individual differences in visual imagery that relies on a key distinction between object and spatial imagery. *Object imagery* refers to representations of the literal appearances of individual objects and scenes in terms of their shape, color, brightness, texture, and size. *Spatial imagery* refers to representations of the spatial relations among objects, parts of objects, locations of objects in space, movements of objects and their parts, and other complex spatial transformations. First, we review cognitive neuroscience and psychology research regarding dissociations in object and spatial–visual imagery. Next, we discuss evidence on how this dissociation extends to individual differences in object and spatial imagery, followed by a discussion showing that individual differences in object and spatial imagery follow different developmental courses. After that we focus on cognitive and educational research that provides ecological validation of the object–spatial distinction in individual differences—in particular, on the relationship of object and spatial–visual abilities to mathematics and science problem solving and then to object–spatial imagery differences between members of different professions. Finally, we discuss applications of the object–spatial dissociation in imagery for applied fields, such as personnel selection, training, and education.

16.2   Object Versus Spatial Imagery: Evidence from Neuroscience and Psychology

Since the 1980s, cognitive neuroscience has provided strong evidence that higher level visual areas of the brain are divided into two functionally and anatomically distinct pathways, the object pathway and the spatial relations pathway (e.g., Kosslyn and Koenig 1992; Ungerleider et al. 1982). The object (occipitotemporal or ventral) pathway processes information about the visual–pictorial appearances of individual objects and scenes, in terms of their shape, color, brightness, texture, and size, while the spatial relation (occipitoparietal or dorsal) pathway processes information about the spatial relations among, and movements of, objects and their parts and complex spatial transformations. The distinction between perceptual processing of object properties versus spatial relations extends to visual mental imagery and working memory (Farah et al. 1988; Kosslyn 1994; Kosslyn and Koenig 1992; Levine et al. 1985; Mazard et al. 2004). For example, Levine et al. (1985) demonstrated that lesions to temporal cortex disrupt performance on a spatial imagery task, but not on an object imagery task. In contrast, lesions to posterior parietal cortex have the reverse effects (see also Farah et al. 1988). Mazard et al. (2004) examined the neural basis of spatial versus object imagery tasks using positron emission tomography (PET) and revealed that superior parietal areas are more strongly activated during

spatial imagery tasks, but the anterior part of the ventral pathway, including fusiform, parahippocampal, and hippocampal gyri, is more active during object imagery tasks. Furthermore, recent evidence suggests that the visual–spatial sketchpad component of working memory consists of separate visual (object) and spatial subcomponents (Courtney et al. 1998; Darling et al. 2006, 2007; Logie and Marchetti 1991; Logie 2003). The above object–spatial dissociation emphasizes that visual–object processing is functionally and anatomically independent from visual–spatial processing, and they are underpinned by separate ventral and dorsal functional organizations, respectively (Borst et al. 2011).

16.3   Dissociation in Individual Differences in Object Versus Spatial Imagery

Despite the cognitive and neuroscientific evidence establishing the existence of object imagery as different from spatial imagery, most of the previous studies on individual differences in visual imagery have focused primarily on understanding individual differences in spatial imagery. These studies attempted to characterize processing differences between participants having high versus low spatial ability for solving, for example, mental rotation (Carpenter and Just 1986), spatial working memory (Miyake et al. 2001), and mechanical, physics, or engineering problems (Kozhevnikov et al. 2007). The results of these studies have suggested that the ability to generate, maintain, and transform spatial images is related to capacity limitations of spatial working memory as well as the availability of central executive resources (e.g., attention allocation) (Miyake et al. 2001). Furthermore, research on the neural underpinnings of spatial ability has revealed an inverse relationship between spatial task performance and associated neural activity (Lamm et al. 1999; Reichle et al. 2000; Vitouch et al. 1997), suggesting that better performance is associated with less neural activity in task-relevant regions (i.e., *neural efficiency*). Vitouch et al. (1997), for example, found that in a spatial comparison task low-spatial-ability participants showed greater activation in right parietal cortex than high-spatial-ability participants. Similarly, Lamm et al. (1999) showed that low-spatial-ability participants showed greater activation in parietal cortex when solving spatial rotation problems and that this activation was more extended into frontocentral regions than that of high-spatial ability participants. Reichle et al. (2000) showed an inverse relationship between functional magnetic resonance imaging (fMRI) blood-oxygenation-level-dependent (BOLD) signal change in parietal cortex and spatial ability (measured independently from performance on the fMRI task) when participants used a spatial strategy to encode and remember text descriptions of objects. Together these studies show that high spatial ability is associated with less activation, and thus more efficient neural resource use, in regions identified as mediating spatial processes.

In contrast to individual differences in spatial imagery, individual differences in object imagery have received less attention in the psychometric, cognitive psychology or neuroscience literature. Surprisingly, contemporary psychology research on individual differences still retains the implicit assumption that visual–spatial ability is the only form of visual intelligence. It has long been expected that this single visual–spatial dimension would predict performance in various professional fields that require imagery and those individuals who are high in visual–spatial ability would excel equally in either science or visual arts (e.g., Gardner and Hatch 1989; Gardner 1999). For instance, Gardner proposed the existence of spatial intelligence (sometimes referred as visual–spatial), which he defined as the ability to perceive the visual–spatial world accurately, and suggested that spatial intelligence is equally important to navigators, pilots, designers, sculptors, and artists. Recently, several psychological and neuroscience studies have provided support for distinctions between visual–object and visual–spatial imagery at the individual differences level (Kozhevnikov et al. 2002, 2005). Kozhevnikov et al. (2005) identified two types of individuals based on their imagery abilities: individuals with high object imagery ability, *object visualizers* (also called *object imagers*), and individuals with high spatial imagery ability, *spatial visualizers* (also called *spatial imagers*). Object visualizers used imagery to construct high-resolution images of the visual properties (e.g., shape and color) of individual objects and scenes. In contrast, *spatial visualizers* tend to use imagery to schematically represent spatial relations among objects, perform spatial transformations, and do not regard surface properties, such as color and texture, as relevant (see also Nicholson and Humphrey 2003; Lacey et al. 2011). Object visualizers were found to outperform spatial visualizers on object imagery tasks (e.g., Degraded Pictures Test, Kozhevnikov et al. 2005) that require generation of high-resolution images, while spatial visualizers were found to outperform object visualizers on spatial imagery tasks (e.g., Mental Rotation Test, Shepard and Metzler 1971, or Paper Folding, Ekstrom et al. 1976) that require spatial visualization and transformation.

Based on the above distinction between visual–object and visual–spatial abilities, a number of theoretically guided assessments of visual–object ability have been recently designed, including objective performance measures (e.g., the Degraded Picture Task, see example in Fig. 16.1) as well as self-report cognitive style questionnaires assessing individuals' preferences for visual–object versus visual–spatial modes of information processing (Blajenkova et al. 2006; Blazhenkova and Kozhevnikov 2009; Kozhevnikov et al. 2005, 2010). These studies consistently demonstrated that all visual–object and visual–spatial ability measures loaded onto two distinct visual–object and visual–spatial factors, respectively (which were also separate from a verbal factor). This indicates that individuals are usually aware of their most efficient mode of visual information processing and that self-report measures (VVIQ—Vividness of Visual Imagery Questionnaire in Marks 1973; OSIVQ—Object–Spatial Imagery and Verbal Questionnaire in Blazhenkova and Kozhevnikov 2009) could be reliably used to identify an individual's particular strengths and weaknesses in the use of object or spatial modes of information processing.

Recently, in order to investigate the neural underpinnings of individual differences in object versus spatial–visual processing, Motes et al. (2008) conducted an

Fig. 16.1 Example of the Degraded Picture Task. (**a**) Example item (umbrella) from the degraded picture task. (**b**) The outline of the umbrella hidden in the picture. The task was to recognize the object depicted in a degraded picture (from Kozhevnikov et al. 2005)
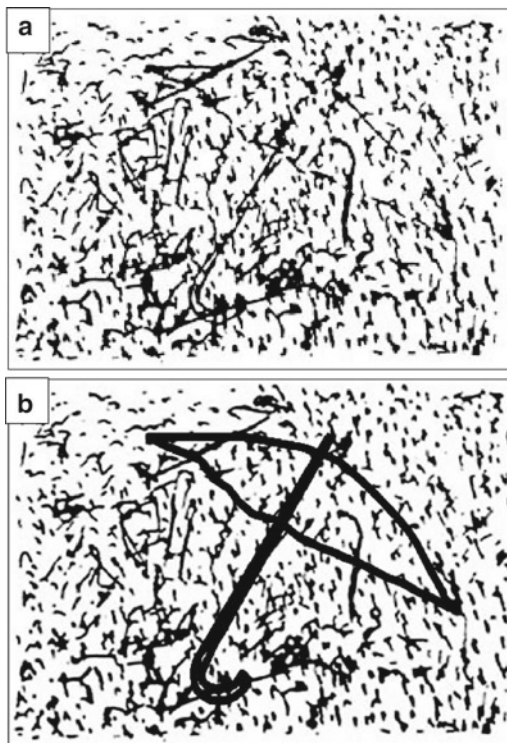
fMRI study in which object and spatial visualizers were scanned while performing an object-processing task in which they were instructed to study and visualize line drawings of common objects to later identify whether different properties of the drawings were present or not. Both spatial and object visualizers showed bilateral task-related activity in the lateral occipital complex (LOC), but object visualizers showed significantly lower LOC activation than spatial visualizers even though object and spatial visualizers performed equally well on the behavioral aspects of the task. Given that LOC mediates object processing (Amedi et al. 2005), the data suggest that the object visualizers used their neural resources more efficiently than spatial visualizers (that is, they show less brain activation in corresponding areas indicating fewer recruitment of object-processing neural resources) while exhibiting the same level of performance at the behavioral level. In addition, object visualizers showed less neural activity in right dorsolateral prefrontal cortex (DLPFC). The DLPFC is associated with executive attentional processes brought online when task demands exceed basic processing capacity (Rypma and D'Esposito 2000). Overall, the results indicated that object processing draws from a relatively independent pool of object-processing resources, and thus constitutes an independent ability that spatial visualizers do not seem to possess to the same degree as object visualizers.

Furthermore, the results of Motes et al. (2008) indicate that high object-processing ability is associated with more efficient use of visual–object resources resulting

in less neural activity in the object-processing pathway. The important implication of this study is that high-object or high-spatial individuals might rely on their processing strengths and fail to engage task-relevant cortical resources if the imagery task does not suit their strengths. Thus, important considerations for future neuroimaging studies are that imagery ability is not a unified construct and that the degree and localization of brain activity will vary considerably depending on participants' imagery abilities and the type of imagery required for the task.

16.4 Developmental Differences in Object Versus Spatial Imagery Abilities

Another line of evidence regarding the dissociation between object and spatial imagery in individual differences comes from developmental research. Blazhenkova et al. (2011) conducted a cross-sectional study in which they examined the development of object and spatial abilities across a wide range of ages (8–60 years old). The participants ($N = 646$) were recruited from schools and universities from three countries with developed educational systems (Russia, USA, and Singapore). The participants were administered a number of tasks testing object imagery ability (the Degraded Picture Task, Kozhevnikov et al. 2005; VVIQ, Marks 1973) and spatial imagery ability (Mental Rotation, Shepard and Metzler 1971; Paper Folding, Ekstrom et al. 1976). The participants' object and spatial abilities were computed by averaging the normalized z-scores on object and spatial imagery tasks, respectively, across all age groups. The analyses of developmental trends across age groups for object and spatial abilities revealed significant age-related changes which were different for each of the abilities (see Fig. 16.2). The development of spatial ability increased in adolescence, followed by gradual decline. In particular, spatial ability measures tended to peak between the ages of 14 and 16, and slowly declined after that, consistent with the results of previous studies (e.g., Vandenberg and Kuse 1978). In contrast, object ability measures also tended to increase in children but did not show the same age-related decline in adults as spatial ability measures did, and even tended to increase with age. This is consistent with previous research which indicated that certain aspects of visual–object processing tend not to decay with age and, moreover, may even increase in older individuals (Campos and Sueiro 1993; Siu et al. 2011; Van Leijenhorst et al. 2007).

Overall, the above studies demonstrated that object and spatial abilities follow different developmental courses. This further supports the idea that these two abilities are different, and also raises important questions for education and training. If, indeed, the critical window for spatial ability development is between the ages of 14 and 16, this would imply that teaching science courses that require spatial ability (such as physics, geometry, or chemistry) might be most effective during these ages. In contrast, because there is no specific critical window in the development of object imagery ability, educators could be more flexible on when courses that rely on object imagery ability (e.g., visual art) are introduced into the school curriculum.
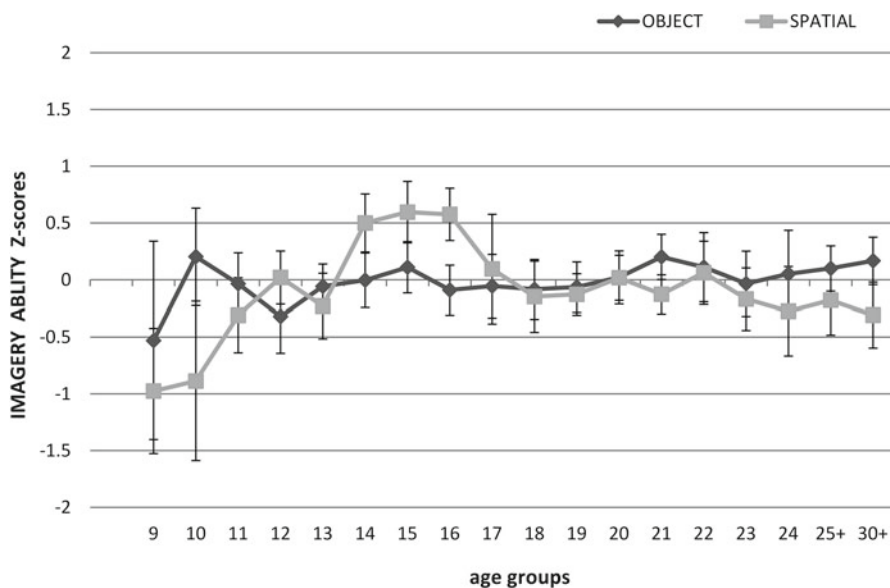
Fig. 16.2 The developmental trajectories for visual imagery abilities: (**a**) object and (**b**) spatial. The bars represent 95% confidence intervals (based on the data from Blazhenkova et al. 2011)

16.5   Object and Spatial Imagery Abilities in Mathematics and Science Education

Numerous studies have been carried out to understand the role of visual representations in mathematics and science learning (e.g., Larkin and Simon 1987; Mandl and Levin 1989; Plass et al. 1998; Winn et al. 1991). However, most studies investigating the effect of visual imagery on learning have treated imagery as a general and undifferentiated skill. We should take into account, however, that since imagery might rely on different types of representations (either object or spatial), different people might have a strong preference for one type or another. In fact, Hegarty and Kozhevnikov (1999) found consistent differences in students' preferences for using spatial–schematic representations that encode spatial relations and object–pictorial representations that encode the visual appearance of the objects. In their study, participants solved mathematical problems and reported on their solution strategies. Use of spatial–schematic representations was associated with success in mathematics problem solving while the use of pictorial representation was negatively correlated with success. Use of schematic representation was also significantly correlated with the students' spatial ability. The results of this research therefore help to clarify the relationship between object imagery, spatial imagery, and math problem solving. While some visual representations promote success, others may present an obstacle to mathematical problem solving.

In another study, Kozhevnikov et al. (2002) reported that object and spatial visualizers tended to employ radically different strategies in science problem solving involving interpreting kinematics graphs. In their study, the authors controlled participants' background in physics by choosing only those object and spatial visualizers who had not taken physics courses either at high school or college level. The participants were asked to visualize and describe the situation depicted on the graph (position versus time). The results of the study showed that object visualizers preferred to use visual–pictorial imagery; they consistently preferred to use global strategies and interpreted the graph literally as a picture of the situation. In contrast, spatial visualizers showed a consistent preference for spatial imagery; they attempted to interpret each interval of the graph successively, part by part. The problem-solving task studied in this article, interpretation of kinematics graphs, required students to interpret a visual–spatial representation as abstract and break it down into different intervals, so that "global" object–pictorial representations hindered success in this task, similar to solving mathematical problems as described in Hegarty and Kozhevnikov's (1999) study.

It is remarkable that a significant group of college students, object visualizers, had difficulty interpreting graphs as abstract schematic representations and instead interpreted them as pictorial representations. Object visualizers will clearly have difficulty solving mathematics problems and interpreting graphs. Instructing students to "visualize" mathematical problems will probably not be successful. How might we best teach these students to represent and solve science and mathematical problems? How can we encourage them to construct spatial representation of the relations between objects in a problem and discourage them from representing irrelevant pictorial details? One possible approach is to teach object visualizers to represent and solve physics and mathematics problems by using verbal–analytical strategies rather than spatial strategies that might be dependent on spatial working memory resources that they do not have. Another possible way of teaching object visualizers is to give them explicit instruction on how object, spatial, and verbal representations relate to each other. Having all these types of representations available and demonstrating how each of them translates into the others might help object visualizers translate concrete pictorial representations into a more schematic spatial form. For instance, microcomputer-based learning (MBL) technologies were designed specifically to pair physical events with their graphical representations in real time and thus provide students with the possibility of exploring connections between them. Students see the graph made by a moving object with the results appearing instantly with each move made by the object. Researchers found a significant change in students' ability to interpret kinematic graphs and overcome graph-as-picture misconceptions after MBL intervention (e.g., Linn et al. 1987; Kozhevnikov and Thornton 2006; Mokros and Tinker 1987; Thornton and Sokoloff 1990). Moreover, it has been shown that teaching students to relate between different types of representation, as in MBL instruction, can significantly increase their performance on spatial tests (Kozhevnikov and Thornton 2006).

We should note, however, that although pictorial images do not contribute to mathematics problem solving and graph interpretation in physics, this type of imagery has been found to be very useful for enhancing memory (Presmeg 1986a), as well

as in social studies classes (Danzer and Newman 1992). Pictorial images can help to illuminate a subject and have been found to have mnemonic advantages (e.g., Paivio 1971; Presmeg 1986a, b, 1992) and to be highly correlated with visual memory measures (e.g., Marks 1973, 1983). Luria's (1982) case study, "The Mind Of A Mnemonist," describes an extraordinary mnemonist, known as "S," who was able to generate images of exceptional vividness and concreteness (his main mnemonic technique was to put different items to be memorized in places alongside streets in Moscow that he knew well and then to take an imaginary walk along these landmarks). However, Luria (1982, p. 388) reported that these vivid images were not flexible and helpful for the mnemonist in tasks dealing with abstract material. S's images were particularly vivid and stable and recurred thousands of times, so they soon became the dominant element in his awareness uncontrollably coming to the surface whenever he touched upon something that was linked to them even in the most general way. Similarly, Aspinwall et al. (1997) found that vivid concrete images may become uncontrollable while solving mathematical problems, "and the power of these images may do more to obscure than to explain" (p. 301). Therefore, it is plausible that object visualizers are especially good at generating vivid pictorial images that may help them succeed in cognitive tasks such as memory tasks, drawing, or painting but that hinder success on mathematical or physics tasks. Thus, the utility of a particular type of imagery depends in part on the task; it is not likely that any type of imagery is necessarily or universally superior to any other type. In summary, the results highlight the need for research that characterizes which type of imagery facilitates learning and reasoning in specific domains.

16.6   Object–Spatial Imagery Dissociations in Different Professional Domains

The previous research leaves open questions about the ecological validity of object imagery. In particular, it does not give a clear answer as to whether object imagery can support abstract thinking of any kind and whether it has more general applications and functional roles in real-life performance rather than supporting only memory functioning. In other words, the question is whether object imagery ability can be considered as an independent component of visual intelligence separate from visual–spatial intelligence. In order to establish an ability as an independent component of intelligence, it must meet the following principal requirements: (1) the ability must play a functional role, that is, it must be related to performance on complex tasks, such as educational or occupational tasks, and not just reflect a narrow ability, such as the ability to score highly on a specific test (Gardner 1999; Gottfredson 1997; Lubinski 2004; Sternberg 1985); (2) it must support high-level information processing, such as abstract representations or symbolic encoding (Carpenter et al. 1990; Galton 1880; Gardner 1999; Gottfredson 1997; Snyderman and Rothman 1987); and (3) it must have unique qualitative and quantitative characteristics,

supported by behavioral and/or neurological evidence that distinguish it from other components of intelligence (Gardner 1999).

Currently, the only widely accepted component of visual intelligence is visual–spatial ability, which is included in most commonly used measures of intelligence (e.g., Stanford-Binet, Roid 2003; Wechsler Intelligence Scale, Wechsler 1997). Spatial ability was found to have all the essential characteristics of intelligence: ecological validity, capacity to support abstract spatial processing in engineering and scientific fields, as well as unique qualitative and quantitative characteristics supported by cognitive psychology research. The tests of spatial ability have been proven to be important criteria for predicting students' achievement in mathematics and a wide range of technical areas (see McGee 1979; Clarkson and Presmeg 2008) and in predicting performance in engineering, mechanics, and physics (Ghiselli 1973; Hegarty and Just 1989; Holliday 1943; Kozhevnikov et al. 2007; Kozhevnikov and Thornton 2006; Smith 1964). The ability to generate vivid colorful images of objects and scenes, however, was long thought to represent an aspect of visual–spatial ability, rather than constitute a separate imagery skill, despite the fact that the instruments assessing individual differences in imagery vividness have failed to establish significant correlations with spatial tasks (for review, see McKelvie 1995).

There is growing evidence that members of different professions might generate different types of visual images and manipulate them in different ways and that visual processing of object (but not spatial) properties might play a crucial role in the creative processes of visual artists (Blazhenkova and Kozhevnikov 2010; Kassels 1991; Miller 1996; Roe 1975; Rosenberg 1987; Winner and Pariser 1985). Visual artists characterize their images as typically pictorial and bright and report preferences primarily for object imagery, while scientists characterize their images as abstract and schematic and report preferences for spatial imagery (Blajenkova et al. 2006; Blazhenkova and Kozhevnikov 2009; Lindauer 1983). Several studies have shown that scientists surpass visual artists on visual–spatial ability tests, which required performing mental spatial transformations, while visual artists surpass scientists on tests which required generation of high-resolution, pictorial images (Kozhevnikov et al. 2005, 2010). For example, Blazhenkova and Kozhevnikov (2010) systematically compared the visual–object and visual–spatial abilities of visual artists, scientists (students and professionals) those in the humanities, and social scientists. Visual artists were significantly more accurate and efficient on all visual–object ability assessments (both self-reports and performance assessments) than science and humanities/social science groups, while scientists were significantly more accurate and efficient on all visual–spatial imagery assessments than the other two groups. Overall, the results indicate that visual–object ability is a reliable and unique predictor of specialization in visual art for college students and professionals. In contrast, visual–spatial ability was related to specialization in science, consistent with previous findings reported in psychometric literature (Ferguson 1977; Hegarty and Kozhevnikov 1999; Pellegrino et al. 1985). Furthermore, visual–spatial ability does not predict specialization in visual art (Blazhenkova and Kozhevnikov 2010).

As for the capacity of visual–object ability to support abstract thinking, the prevailing view within the literature, beginning with Galton (1880) and persisting even in contemporary literature, has been to associate visual–object ability with concrete

visual thinking, low intelligence, and an inability to form abstract visual representations (Aspinwall et al. 1997; Twyman 1972; Brewer and Schommer-Aikins 2006). However, historical analysis suggests that visual art might not only portray the concrete visual appearances of objects and scenes (e.g., landscapes or portraits in Renaissance art) but also represent abstract content, such as pure emotions and concepts using color and shape (e.g., Cubism and Abstract Expressionism) (Miller 1996). In order to investigate this issue further, several researchers (Blazhenkova and Kozhevnikov 2010; Kozhevnikov et al. 2005) compared how individuals, depending on their proficiency (due to experience or natural ability) in object versus spatial information processing, interpreted abstract visual–spatial representations, such as science graphs, and abstract visual–object representations, such as modern art. Scientists interpreted kinematic graphs in an abstract way, while visual artists interpreted them literally, as pictures (Kozhevnikov et al. 2005; Blazhenkova and Kozhevnikov 2010; see Fig. 16.3). If pictorial visual–object imagery is simply a concrete form of spatial imagery, it follows that scientists' proficiency in spatial processing would also help in interpreting visual–object information. If individuals of high proficiency in spatial processing are unable to do so while individuals of high proficiency in object processing are, this would suggest that the visual–object domain conveys a type of abstract information distinct from visual–spatial abstract information. Blazhenkova and Kozhevnikov (2010) compared how visual artists versus scientists interpreted abstract visual–object information (modern abstract art). Their results showed that visual artists tended to interpret abstract art as abstract representations; they referred to the paintings in terms of conceptual and emotional content that was not directly depicted but was related to the ideas expressed by artists. In contrast, scientists tended to interpret abstract art literally, sequentially, using spatial imagery strategies, which led them to concrete interpretations of the painting in terms of its surface features, such as colors or concrete objects resembling the shapes in the paintings, with less reference to emotional content of the pictures. The results indicate that scientists' proficiency in spatial processing is not sufficient for supporting abstract representations in the visual–object domain suggesting that visual–object imagery cannot merely be considered a concrete form of visual–spatial reasoning. Overall, the results indicate that object imagery can support abstract visual–object representations in the same way as spatial processing supports abstract visual–spatial representations and that the visual representations contained in abstract art indeed constitute a unique and meaningful symbolic system, irreducible to that used in the visual–spatial domain.

Finally, Blazhenkova and Kozhevnikov (2010) demonstrated qualitative differences between visual–object and visual–spatial imagery processes described by professionals across all stages of visual processing (*image generation, inspection, maintenance*, and *transformation*). At the *generation stage*, visual artists describe their images as vivid, pictorial, rich in color, detail, and texture, and generated holistically, as single perceptual units, with fine details present upon generation, and content that is not always deliberately generated. In contrast, scientists described their images as mostly schematic, reflecting primarily the structural properties of objects and scenes. Scientists' images tended to be generated intentionally and primarily in a sequential way, part by part.

Fig. 16.3 Example of
responses to a kinematic graph
problem (**a**) given by a visual
artist (**b**) and a scientist (**c**)
(from Kozhevnikov et al. 2005)

A woman walking towards an escalator on the second floor of a shopping mall. She goes down the escalator, then she frollicks toward her favorite shoe store.
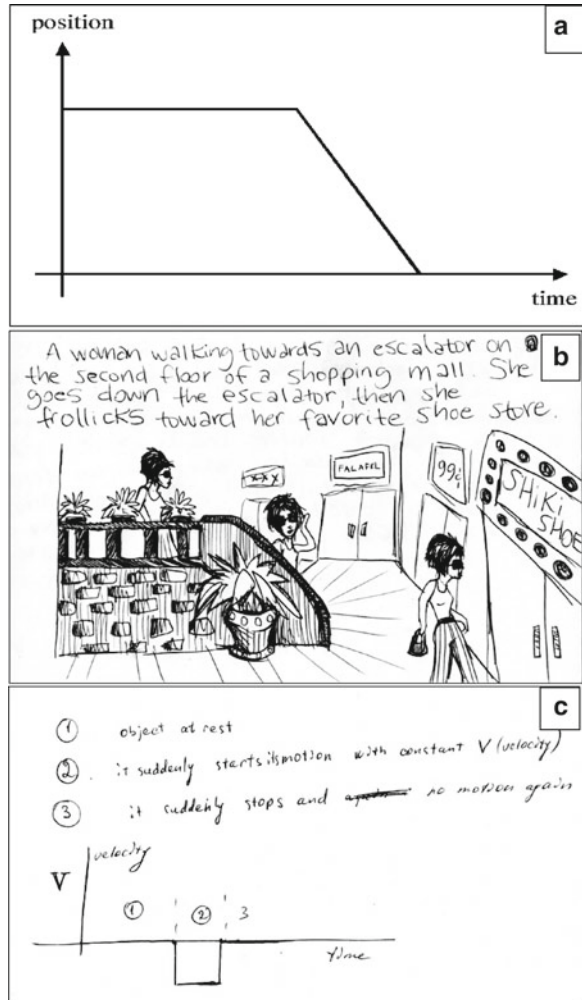
During *the inspection stage*, visual artists tend to intentionally inspect their visual images in detail in order to explore their images' meanings, which are often ambiguous and multifaceted. In contrast, scientists' images are less likely to be purposely inspected, since scientists' images are usually generated specifically for rational, logical tasks, and thus their meanings tend to be unambiguous and apparent upon generation. During *image maintenance*, visual artists' images are stable and often persistent. Visual artists tended to maintain their images effortlessly, in contrast to scientists, who generally maintain only specific parts of their images through conscious effort. At the *image transformation stage*, many visual artists reported that their images were highly resistant to transformations. In cases when they do perform transformations, they tended to transform primarily visual–object properties (e.g., surface properties like color and shape) of

their images, but not purely visual–spatial properties (e.g., rearranging the visual–spatial structure). Scientists, in contrast, reported themselves to be very efficient in spatial transformation and did not regard surface properties as relevant. Overall, the above findings suggest that visual–object imagery has unique qualitative characteristics at all four stages of image processing and that the properties of visual–object imagery at different stages of processing might be seen as emergent properties of the holistic nature of visual–object processing. Likewise, the properties of visual–spatial processing at different stages might be seen as emergent from the sequential nature of visual–spatial processing.

The differences between the holistic nature of visual–object processing and the sequential nature of visual–spatial processing as reported by visual artists and scientists, respectively, are consistent with cognitive neuroscience evidence on the distinction between object and spatial imagery. This suggests that object images are generated by pattern activation in a visual buffer (i.e., topographically organized areas in the occipital lobe, V1 and V2) on the basis of information stored in long-term memory and encoded globally as discrete perceptual units (Kosslyn 1994; Kosslyn et al. 2006). In contrast, spatial images are generated sequentially, part by part, via successive shifts of attention to represent spatial relations between objects or their parts. In general, global encoding and processing of images by the visual–object system would hinder flexible image transformations, but facilitate image generation and recognition, since the time needed to generate and activate an object image should not depend on an image's complexity. In contrast, sequential processing of images by the visual–spatial system facilitates flexible spatial transformations. Since scientists comprehend the structure of visual information by parts, their visual–spatial images seem to be more flexible and transformable. In contrast, visual artists' images are encoded as single, global perceptual units which are not easily transformable. In other words, parts of the image are locked into place with one another such that one part is difficult to transform without transforming the others (see Blazhenkova and Kozhevnikov 2010 for detailed discussion). Thus, both object and spatial imagery are uniquely suited to effective visual processing at different stages for different tasks.

16.7 Trade-Off Between Spatial and Object Imagery Abilities

Research indicates relative independence between the ventral and dorsal visual pathways, associated with object and spatial–visual processing, respectively (Courtney et al. 1998; Ungerleider and Mishkin 1982; Mazard et al. 2004), although this does not necessarily imply dissociation in individual differences in imagery.[1]

Recent studies revealed that there is a trade-off between object and spatial imagery abilities at the individual difference level, rather than independence

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[1] Object and spatial imagery abilities might be independent but also might tap the same underlying visual imagery ability. In the latter case, this underlying ability would not rely exclusively on object or spatial pathways but would also depend on other brain areas involved in visual processing (e.g., prefrontal cortex, early visual areas).

(Kozhevnikov et al. 2005, 2010). For instance, Kozhevnikov et al. (2010) studied five age groups with different professional specializations (visual artists, architects, scientist, and humanities) and reported that participants with above-average object visualization abilities had below-average spatial visualization abilities, and the inverse was true for those with above-average spatial visualization abilities. Visual artists had above-average object imagery and below-average spatial imagery skills, and the opposite pattern was seen in scientists. Humanities professionals were not different from average on either object or spatial imagery, and architects were above average only in spatial imagery (and no different than average in object imagery). No group showed both above-average object and above-average spatial visualization abilities, supporting the existence of the trade-off between object and spatial imagery abilities. Furthermore, within each age group, those specializing in different visual fields (art, science, and architecture) demonstrated similar total visual-processing resources which were differentially distributed across object and spatial visualization abilities.

Figure 16.4 illustrates the distribution of object (*Zobj*) versus spatial (*Zspat*) abilities in different professional groups. The first score, *Zobj+Zspat*, was created by adding *Zobj* and *Zspat* scores to reflect the overall amount of visualization (object and spatial) resources. The second score, *Zobj−Zspat*, was created by subtracting *Zspat* from *Zobj* to reflect the direction and magnitude of the trade-off between object and spatial visualization abilities. Only humanities professionals had a significantly lower *Zobj+Zspat* score than the other groups. The other three groups (visual artists, scientists, and architects) did not show any significant differences.[2] As for the *Zobj−Zspat* score, significant differences were found between the groups, indicating the largest magnitude of trade-off in scientists (favoring spatial) and visual artists (favoring object) and the smallest in architects and humanities professionals. The authors obtained similar results for other age groups including groups of gifted children of ages 10–13 specializing either in art or science. While total object and spatial visualization resources increased with age and experience, the trade-off relationship between object and spatial visualization abilities did not.

The origin of the trade-off between object and spatial abilities remains a puzzle. The authors speculated that the trade-off originates through a bottleneck, which restricts the development of overall visualization resources, rather than through preferential experience in one type of visualization. Future neuroscience studies might shed light on an interaction between attentional resources and visualization abilities and provide us with better understanding about how visual imagery might differ between individuals. From an applied perspective, the importance of these findings is that object and spatial visualization abilities might not develop independently in those with high ability and talent in visual professional

[2] Humanities and social science students and professionals were included in Blajenkova et al. (2006) and Blazhenkova and Kozhevnikov (2010) to serve as a control professional group, since the humanities and social sciences lend themselves to visual forms of information processing less readily than do natural sciences. In addition, the imagery used by humanities/science professionals is more along the lines of logical representations of concepts and relationships among concepts rather than representing the arrangement of physical objects or graphs and data models (e.g., Wai et al. 2009).
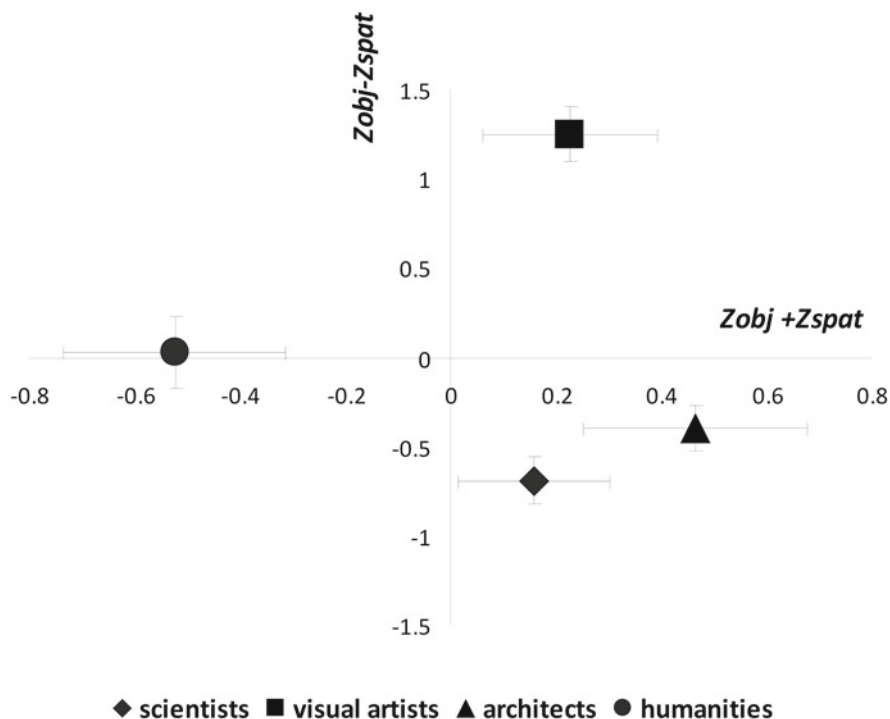
Fig. 16.4 Zobj−Zspat versus Zobj+Zspat scores for different specialization subgroups of professionals. The bars represent ±*SEM* (from Kozhevnikov et al. 2010)

fields. Thus one important future research direction would be to investigate how specialized education in these fields might foster different types of visualization and what the best age would be to start specialized training that builds on these early-age predispositions.

16.8   Gender Differences in Object Versus Spatial Imagery Abilities

Research has demonstrated that females tend to outperform males on imagery vividness ratings (McKelvie 1995; Campos and Sueiro 1993), report higher use of object imagery, and outperform males on a number of tasks that require object imagery ability (e.g., shape recognition) (Blajenkova et al. 2006; Blazhenkova and Kozhevnikov 2009; Kozhevnikov et al. 2005). Males tend to outperform females on tasks that require spatial visualization and transformations such as mental rotation (Collins and Kimura 1997; Linn and Petersen 1985; Voyer et al. 1995). The opposite pattern of gender difference for visual–object and visual–spatial imagery provides

additional support to the idea that visual–object and visual–spatial imagery involves different cognitive processes. However, the results of recent studies also showed that difference between spatial and object visualizers cannot be reduced to gender differences. Numerous men were reported to be object visualizers, and numerous women were identified as spatial visualizers (Blajenkova et al. 2006; Blazhenkova and Kozhevnikov 2009; Kozhevnikov et al. 2005). Furthermore, Blazhenkova and Kozhevnikov (2010) reported that specialization is a stronger predictor of object and spatial imagery abilities than gender.

16.9 Further Applications of Object–Spatial Imagery Research for Education and Training

One important direction for future research would be to further develop visual–object intelligence assessments. Current IQ tests either ignore visual–object ability or assess visual–object and visual–spatial ability as a unitary construct (mostly measuring spatial rather than object ability). Research by Kozhevnikov et al. (2005) investigated the relationship between the object–spatial dimensions and traditional IQ measures, including Raven's Matrices (Raven et al. 1998) and Verbal WASI, and found that WASI is unrelated to both visual–object and visual–spatial abilities, while performance on Raven's matrices tends to correlate only with visual–spatial ability (see also Blajenkova et al. 2006). Research has, in general, noted that visual ability was a neglected dimension in talent searches, despite its unique predictive validity (Webb et al. 2007), and criticized the existing system of identifying giftedness that is currently mainly restricted to verbal and mathematical ability, despite the purported intent of seeking and developing talents across multiple dimensions. Although some talent search programs include assessments of visual–spatial intelligence (e.g., Raven Matrices; Dental Admission Test, DAT Users Manual 2011), there are currently no assessment procedures for visual–object intelligence.

Similarly, our findings strongly suggest the need to develop appropriate training procedures to improve performance on visual–object tasks and comprehension of visual–object representations. While much attention has been paid in educational research to training visual–spatial abilities (e.g., Lohman and Nichols 1990; Lord and Holland 1997; Pallrand and Seeber 1984; Kozhevnikov and Thornton 2006), training of visual–object abilities has not received as much attention. Assessment and training procedures for visual–object ability would be of great value for identifying visual–object gifted individuals and helping them to realize their full potential and efficiently develop their skills in a professional field.

Recently there has been a great increase in the importance of object information and object-abstract representations in various media, including educational media, movies, advertisements, and contemporary art (Manovich 2001). Also contemporary media tends to use rapidly presented, emotionally charged visual stimuli that need to

be processed holistically and quickly. Thus, in contemporary society, due to new task demands, the role of object imagery has been increasing, and thus, recognizing visual–object ability as a type of intelligence, separate from spatial, and developing individuals' visual–object abilities might be critical not only for success in visual arts but also in a wide range of professions and in everyday performance. In summary, the research reviewed in this chapter indicates the separate and independent status of object and spatial imagery abilities and suggests the importance of distinguishing between them for research, education, vocational guidance, and other applied fields.

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Chapter 17
Motor and Visual Imagery in Sports

Jörn Munzert and Britta Lorey

Abstract Mental practice routines play an important role in many different sports, not only for the acquisition of motor skills but also for preparation prior to competitive events and rehabilitation after sport injuries. Imagery techniques in sport are used for different purposes, as outlined by the Model of Imagery Use in Sports [Martin et al. (Sport Psychologist 13:245–268, 1999)], to improve skill acquisition, motivation, and sport confidence and to reduce anxiety. Individual differences in imagery abilities have to be considered to understand the possible effects of mental practice in the sports context. It has been revealed that a differentiation of expertise levels (experts and novices) and skills (closed and open) is important for the categorization of imagery effects in sport. Experts are more experienced in processing movement sensations compared with novices and can, therefore, generate kinesthetic imagery more easily. Open and closed skills differ in their predictability of the environment. Compared with closed skills, open skills specifically require the ability to imagine external events and changes to the environmental conditions. It has been shown that different forms and functions of imagery prove to be effective for the above-mentioned functions depending on the characteristics of different sports and the expertise level of athletes.

Keywords Mental practice • Imagery use • Imagery perspective • Mental chronometry • Skill acquisition • Confidence • Anxiety

J. Munzert, Ph.D. (✉) • B. Lorey, Dipl. Psych., Ph.D.
Neuromotor Behavior Lab and Bender Institute for Neuroimaging,
Institute for Sport Science, Justus Liebig University Giessen,
Kugelberg 62, 35394 Giessen, Germany
e-mail: joern.munzert@sport.uni-giessen.de; britta.lorey@sport.uni-giessen.de

17.1 Enhancing Performance in Sports Through Imagery

The application of mental practice routines in sport settings can draw on a long tradition in sports and sports sciences (Puni 1961; Richardson 1967a, b) and has been a subject of much attention and even fascination due to its importance for top athletes (Greenleaf et al. 2001; Mahoney and Avener 1977). Imagery techniques in a broader sense have probably been used to enhance performance in all sports, on different skill levels, for different age groups, and using different implementations of specific imagery scripts. While acknowledging this diversity of applications, one can differentiate two main purposes of imagery in the field of sports. The first refers to the motor learning domain. Here, athletes try to learn new skills, bring their often highly trained motor techniques to perfection, or relearn skills after sport injuries (Hall 2001). The second focuses on actual performance, often while preparing for the next competition or sometimes for the next trial. One can observe this latter function of mental preparation in competitions when downhill skiers or bobsledders are anticipating their intended course. Such athletes imagine their forthcoming performance in real time to "get a feeling" for how to respond to the requirements of a task. Normally, these situations reveal no intention to produce long-term learning effects, although the occurrence of learning cannot be ruled out. However, the main focus is on actual achievement and, in particular, mental imagery is directed toward motivational processes that may enhance individual achievement (cf. Paivio 1985).

Sport psychology reveals a wide range of routines for mental practice. These share a common content, namely, imagery of an action. It is important to note that behavior in sports is mostly goal directed. Therefore, the basic content imagined by an athlete is an action containing a goal that has to be achieved by means of movements. The specific kinematics of the movement may serve as an important aspect of the imagery. Although one can find typical examples in which the main focus is on biomechanical aspects of a movement, individual images in sports typically seem to address more environmental aspects. Athletes imagining a badminton serve also have to imagine the racket and the shuttlecock. However, further environmental cues have to be anticipated as well. These may be the height of the net, the playing field, or the opponent's behavior. When badminton players are asked to describe their badminton-specific images, these differ markedly in terms of the specific imagery content, such as the aspect of the moving body, the net, or the shuttlecock (Munzert et al. 2000). It has been suggested that these differences rely on individual experiences and the individual's skill level. The consequence of this theoretical notion is that what is actually imagined depends on the level of individual motor skills, imagery abilities, and imagery preferences (Munzert and Hackfort 1999). We shall discuss these topics extensively in the following sections.

Athletes may also differ in terms of which imagery modality they typically use. This is only to be expected if the focus is on imagery of individual actions. Traditionally, two typical modalities for imagery of sports behavior are discussed in the literature: the motor or kinesthetic modality and the visual modality. Against this background, classical neuroscientific literature has placed more emphasis on motor imagery. Motor imagery refers to the individual feeling of being the agent of

an action and imagining how it would feel if one were to actually perform it without simultaneously moving one's limbs. Sport psychology uses the terms "mental image" and "motor imagery" somewhat differently to neuroscience. We have suggested that the term motor imagery denotes imagery processes requiring participants to imagine their own actions regardless of the imagery modality but with an emphasis on agency (Munzert et al. 2009; Munzert and Zentgraf 2009). Motor imagery includes two visual imagery perspectives (first- or third-person perspective) and relies mostly on kinesthetic images. It is specifically the kinesthetic sensations during imagery that let athletes feel that they are the agent of their image.

However, visual imagery also seems to be important for motor skills. Other sensory modalities might also play an important role. One of these is auditory imagery. Auditory cues seem to be relevant for action execution. In sports, they are used to interpret individual feedback. Think about a downhill skier. Auditory cues deliver additional evidence on the precision of a skiing technique. For example, an expert skiing on an icy slope can identify specific auditory cues that can be used as a feedback about the precision of a technique. The same holds for the exact dipping of oar blades in rowing. Specifically for rowing experts, these auditory cues seem to provide important information about the ongoing movement, because they normally do not see the blades dipping. Indeed, in a questionnaire study with 102 badminton players, 39% reported auditory imagery when imaging badminton rallies (Munzert et al. 2000).

Hence, sport-specific images can include a wide range of different imagery modalities and content. However, these modalities and content are not based on distinct and isolated processes, but are combined into a single holistic inner perception. They are weighted for different purposes by applying different manipulations, and they are modulated by the athlete's personal experiences and preferences (Munzert et al. 2009). One important tool in the weighting process is the specific imagery instruction. For example, instructions can emphasize the modality, or they can focus on some specific detail of the movement kinematics. Nonetheless, there is no direct evidence on what happens internally when an athlete applies imagery (Munzert and Zentgraf 2009). Of course, evidence can be gained from verbal reports, from mental chronometry, and from neuroimaging. But these methods all provide only indirect evidence on the underlying processes. For example, it has to be assumed that an athlete more or less follows the mental imagery instruction. In this context, it is an interesting footnote that coaches in the field attach great importance to finding optimal instructions, whereas experimental studies on mental training rarely report the literal instructions used in an experiment (Munzert et al. 2009).

17.2   Imagery Abilities

The use of imagery to enhance sport performance has been of major interest to applied sport psychologists and athletes. First and foremost, imagery is used to improve motor task performance and learning (Feltz and Landers 1983). Its benefits, however, often depend on an individual's ability to create vivid motor images—indeed, there seems

to be a relationship between imagery ability and the motor improvements to be seen following motor imagery (Munroe et al. 2000). Several psychological questionnaires and experimental paradigms have been developed to assess such motor imagery abilities. Subjective reports characterize imagery ability in terms of vividness, i.e., the clarity and realism of the imagery experience. This is associated with the formation and maintenance of the image in working memory. Thus, the vividness of a resulting image actually reflects the richness of the representation in working memory (Baddeley and Andrade 2000). Alternatively, the mental chronometry paradigm assesses imagery abilities by comparing the durations found when participants perform the same movements either actively or mentally. In the following paragraphs, we shall discuss these approaches in more detail.

17.2.1 Subjective Measurements of Imagery Ability

A central problem in imagery research and its applications is the difficulty in assessing the use of imagery or determining differences in individual's capability to imagine movements (Hall et al. 1985). Several scales have been developed to describe and test individual imagery ability. Early assessments of imagery were based on the Gordon Test of Visual Imagery Control and the Betts Test (cf. Richardson 1969). A more recent assessment of imagery ability was developed by Marks (1973). This is the 16-item version of the Vividness of Visual Imagery Questionnaire (VVIQ). This scale asks people to rate the vividness of their imagery with respect to four aspects of four familiar scenes. Turning to the measurement of the imagery of movement, one prominent self-report questionnaire is the Movement Imagery Questionnaire (MIQ) developed by Hall and Pongrac (1983). This questionnaire was constructed in order to obtain an appropriate method for measuring visual and kinesthetic components of the imagery process. The MIQ addresses whole-body movements. Participants are instructed to produce a specific movement before being asked to imagine the movement either visually or kinesthetically. The ease of using imagery is assessed on a 7-point scale. In 1997, the MIQ was revised, resulting in a shorter version, the MIQ-R, containing only eight items (Hall and Martin 1997). Another instrument that is often used to measure motor imagery abilities is the Vividness of Motor Imagery Questionnaire (VMIQ) developed by Isaac et al. (1986). The VMIQ is a 48-item questionnaire in which subjects are asked to use a 5-point scale to rate their imagery for a series of activities from a first-person perspective (imagine oneself performing the respective activity: kinesthetic subscale) and a third-person perspective (imagine someone else doing the activity: visual subscale). In contrast to the MIQ, subjects are not asked to perform the movements.

In 2008, Roberts, Callow, Hardy, Markland, and Bringer developed a modified and psychometrically valid version of the VMIQ, the VMIQ-2. One of their main goals was to alter the instructional set of the VMIQ so that first-person visual imagery and kinesthetic imagery could be assessed as separate modalities while assessing external self visual imagery as third-person-perspective imagery. This approach takes

the specific imagery modality and perspective conceptualizations into account (Hardy and Callow 1999) in order to provide a more comprehensive and psychometrically acceptable assessment of movement imagery ability (Roberts et al. 2008). It represents the present state of the discussion on modalities and perspectives as presented in the first section of this chapter.

A further imagery scale is Malouin et al.'s (2007) Kinesthetic and Visual Imagery Questionnaire (KVIQ). This was developed for persons who have to be guided when rating imagery and who are unable to perform complex movements by themselves (e.g., patients). This scale also assesses visual and kinesthetic dimensions of imagery. As in the MIQ, the testing involves actual performance as well as a rating of visual and kinesthetic imagery. The KIVQ is, however, not self-administered by the patient.

Self-report data are often criticized for lacking validity and reliability and being subject to response biases. Therefore, the use of subjective scales has been augmented by several experimental paradigms designed to obtain further objective data on imagery performance.

17.2.2 *Mental Chronometry and Mental Rotation: Behavioral Variants Determining Imagery Performance*

Experimental paradigms such as the mental chronometry paradigm or mental rotation tasks have applied other ways of assessing imagery ability and imagery quality that are considered to deliver a more objective test of the underlying processes. The central argument for the mental chronometry paradigm is that similar durations can be found when participants perform the same movements either actively or mentally, thus indicating the relevance of motor representations in motor imagery (Decety 1996; Jeannerod 1994). In mental rotation paradigms, subjects are shown stimuli, such as different 2-D letters or 3-D structures made from cubes that differ in their spatial orientation (Shepard and Metzler 1971). They are then asked to perform spatial manipulations of these stimuli to identify the congruency of the items. Imagery is assumed to play an important role in solving these tasks (Hall et al. 1985).

Turning to mental chronometry, one initial finding is that imagined actions retain the same temporal characteristics as executed actions. Decety et al. (1989) conducted a study of actual and mental durations of movements by examining different walking distances. Their results revealed strong correlations between mean active and mean mental durations. A correspondence between actual and imagined durations has also been found for a variety of movements such as writing, drawing, or pedalo boating (Decety and Michel 1989; Munzert 2002; Papaxanthis et al. 2002). It has also been demonstrated that task complexity (conceptualized in Fitts' law, a model which predicts that the time required to rapidly move to a target, e.g., during pointing, depends on the distance to and size of the target (Fitts 1954)) influences both real and imagined movements (Decety and Jeannerod 1996; Sirigu et al. 1995, 1996; see also Chap. 6). Other studies using even more complex tasks have delivered evidence for

dissociation between actual and mental durations with mental tasks taking longer than actual tasks. Such evidence comes specifically from tasks in the sports domain such as golf putting (Orliaguet and Coello 1998), playing badminton rallies (Munzert 2008), performing floor routines in gymnastics (Calmels and Fournier 2001), and springboard diving by novices and intermediates—but not by experts (Reed 2002). It has been shown that differences between actual and mental durations can be reduced by motor expertise, i.e., the dissociation tends to disappear (Munzert 2008; Reed 2002). These results of expertise studies suggest that this paradigm might be used to gain insight into the quality of imagery processes and the underlying motor representations as experts gain a differentiated motor representation of a movement by motor experience. The observed decreased difference between actual and mental duration might reflect more elaborated motor representations.

It has also been argued that the mental rotation paradigm is another promising objective test for imagery ability (Hall et al. 1985). This is because the main strategy for solving these tasks is based on imagery processes. The mental rotation paradigm has been applied for rotations of letters, 3-D structures, hands, legs, and whole-body figures (Cooper and Shepard 1975; De Lange et al. 2006; Jola and Mast 2005; Parsons 1987, 1994). Several studies have shown that motor constraints influence the time course of decisions on the orientation of body parts. For example, longer reaction times were found for anatomically inaccurate body parts or positions (Petit and Harris 2005; Petit et al. 2003; Sauner et al. 2006). In addition, judging imagined prehension movements that varied in the level of difficulty due to the opposition axis of the fingers revealed longer reaction times for difficult movements, showing that motor imagery reflects the biomechanics of the arm (Frak et al. 2001). A recent study by Steggemann et al. (2011) examined whether motor expertise enhances solving a mental rotation task. Experts (athletes with several years of experience in their sports of expertise, such as artistic gymnastics, aero wheel gymnastics, and trampolining) and novices for rotational movements were tested in two conditions of a mental body rotation task: a left–right judgment evoking a perspective transformation and a same–different judgment evoking an object-related transformation. Results showed that motor experience selectively influenced performance in the mental body rotation task with the left–right but not with same–different judgment. More precisely, motor expertise ameliorated performance only when human figures were presented in what were, for nonexperts, unfamiliar upside-down body orientations. In conclusion, the mental rotation paradigm relies on advanced implicit measures because rotation times were measured and then interpreted as imagery abilities or were related to representations (Steggemann et al. 2011). However, the performance advantages of experts shown by Steggemann et al. (2011) might suggest the possibility of using mental rotation tasks to gain insight into mental imagery abilities.

In sum, the data originating from studies on mental chronometry and mental rotation (e.g., Decety and Jeannerod 1996; Sirigu and Duhamel 2001) support the assumption that motor imagery using motor representations is used to solve these tasks. Thus, it would seem to be reasonable to use these tasks to assess imagery quality and ability. The next step will be to examine the possible neural substrate of these phenomena more closely.

17.2.3   *Neural Substrates of Vivid Imagery*

Guillot et al. (2008) have examined how individual differences in imagery ability mediate neural activity during motor imagery by using functional magnetic resonance imaging (fMRI). In order to differentiate between good and poor imagery abilities, a series of psychological, behavioral, and neurophysiological tests were administered prior to the fMRI scanning to evaluate subjects' MI ability. The authors used physiological measures of the autonomic nervous system (ANS) during motor imagery of several actions to test the subject's abilities to produce MI. Simultaneously, the temporal congruence between real and imagined actions was evaluated (mental chronometry paradigm). After each imagery trial, subjects were then asked to evaluate the vividness of their imagery (auto-estimation). Furthermore, each participant completed the MIQ-R (Hall and Martin 1997). With these data, a global imagery score was calculated for each participant, using the following formula: (ANS score + MIQ-R   score + auto-estimation   score) − (mental   chronometry   score). Afterwards, extreme groups of good and poor imagers were defined. The extreme-group comparison of the fMRI data revealed that both poor and good imagers activate neural networks that involve motor-related areas such as the posterior parietal and premotor regions. This effect was more pronounced for individuals with good compared to poor imagery, with good imagers displaying greater activation in the parietal and premotor regions.

   Within this framework, Lorey et al. (2011) were the first to reveal a positive correlation between imagery vividness and activation within the motor and motor-related areas while using a within-subject design. They demonstrated a close parametric relationship between the imager's perceived vividness of motor imagery on a specific trial and activation in motor areas, especially within the parieto-premotor network. Thus subjective data assessed with a psychological evaluation tool (e.g., a rating scale) correlated closely with neural activation assessed by fMRI. Combining these findings, it might be suggested that neural activation within the motor network, especially within parieto-premotor areas, varies inter- and intra-individually as a function of perceived motor imagery vividness. Thus, psychological assessments and introspection offer a promising and informative method for studying imagery abilities because of their connection to neural activity within motor areas.

17.3   Applications in Sports

In this section, we shall review the evidence on how imagery is used in sports and how imagery enhances individual performance in different sport settings. When looking at skill acquisition, we shall extend the view to learning situations outside of sports. It is important to note here that the empirical evidence relies on different methodological approaches. Whereas research on the influence of imagery on skill acquisition is

basically grounded in experimental or quasi-experimental study designs that typically contain control groups, the situation is different for studies on the imagery–performance relation. Here we find descriptive and correlative studies that describe how the use of imagery strategies influences psychological moderators or, more directly, performance. This research practice does not indicate a lack of methodological rigor; it is more a reflection of practical restrictions. First, most imagery practice in sports is based on spontaneous behavior by athletes who are convinced about the efficacy of their individual style of mental practice and who receive massive individual feedback during this practice. They can be considered to be experts on imagery, and they constitute a rich source for assessing basic mechanisms of visual and motor imagery. Second, it is often difficult to conduct experimental studies with top athletes, because they can only be persuaded to participate when a positive outcome is guaranteed. Obviously this is not possible for every experimental study. Third, most studies can draw on only a limited number of top athletes. This restricts control group designs requiring a greater number of participants in a study. Nonetheless, expertise research (Williams and Ericsson 2005) has shown that detailed studies on the use of certain strategies and neurocognitive mechanisms can elucidate how interventions can be better motivated.

Here, we shall start with a review of how imagery is used in different sports settings. We shall then highlight research in the skill acquisition domain. Finally, we shall outline how imagery impacts on actual performance by influencing confidence.

17.3.1 Imagery Use in Sports: Imagery Use Model

Imagery techniques such as mental practice are used in different sports for different purposes and both unsupervised and under the supervision of mental coaches. This makes it crucial for applied imagery research to examine the frequency, function, and situational context of imagery use in sports. Hall et al. (1990) asked 381 athletes from six different sports (American football, soccer, ice hockey, squash, gymnastics, and figure skating) to report their imagery use. The authors were interested primarily in the situational context, that is, where and when the athletes applied imagery. They found that skill level correlated with the frequency of imagery use. Athletes competing at a provincial or a national level reported a greater use of imagery during training sessions and also before a competition compared with athletes at a lower competitive level. They also reported more structured imagery sessions and better images of the entire skill. Concerning the classical distinction between closed and open skills which differ in the predictability of the environment (Schmidt and Lee 2005), gymnasts and figure skaters (closed skills) reported kinesthetic imagery more often than soccer, American football, and squash players (typical examples of open skills). Salmon et al. (1994) reported a relatively equal frequency for the use of visual and kinesthetic imagery in a sample of 362 soccer players but a higher frequency of kinesthetic, compared with visual feedback, in gymnasts and figure skaters. Barr and Hall (1992) examined the imagery use of 348 rowers. Elite compared

with novice rowers reported more vivid images from a first-person perspective and better kinesthetic images. Elite rowers reported better feelings about "the blade through the water," "specific muscles in action," "personal body swing," and "drive and run of the shell" (Barr and Hall 1992, p. 252). This illustrates superbly how experts are able to generate kinesthetic images.

The most prominent attempt to systematize functions of imagery in sport goes back to Paivio (1985) who differentiated between cognitive and motivational functions of mental practice (see also Watt et al. 2008). He further differentiated a specific and a more general level of application for both categories. This resulted in an analytic model of imagery use in sports. The Cognitive-Specific (CS) factor refers to the mental rehearsal of a specific motor skill as is often found in mental practice routines in the acquisition of motor skills in sport or rehabilitation. In contrast, the Cognitive-General (CG) factor focuses more on tactical aspects of the sport behavior. CG takes the situational context of the behavior into account. Even if this sometimes seems to be a more gradual distinction, it addresses a well-established suggestion in sports. Additionally, the Motivation-Specific (MS) factor refers to imagery use aiming to enhance a specific goal attainment, whereas the Motivation-General (MG) factor refers to functions of self-confidence, mastery of anxiety, and—more generally—the enhancement of mental toughness.

This model served as a basis for developing the Sports Imagery Questionnaire (SIQ) (Hall et al. 1998, 2005). Factor analyses during the development of the SIQ revealed that the factors CS, CG, and MS could be identified properly but that MG had to be split into two subcategories. Arousal, MG-A, contains the function of arousal control whereas Mastery, MG-M, focuses more specifically on the athlete's motivational states. These factors define the basic functions of imagery in sport settings and also reflect the desired outcome that athletes and coaches associate with these functions. The differentiation of imagery functions has been fed into a more complex model of imagery use in sports (Martin et al. 1999). This contains the sports situation in which imagery is applied, for example, training, competition, or injury rehabilitation; and it includes imagery abilities as a moderator variable for the outcome of imagery functions. An adapted and modified version of this model is depicted in Fig. 17.1. The imagery types as examined with the SIQ may serve different purposes depending on the situational context. For example, CS may serve as means of learning in a preseason training session and also as means of focusing on the pivotal trial in a competition. Expectations about the outcome of CS in both situations may differ. However, this does not predicate that CS in a given situation has only the intended effect. If an athlete imagines himself or herself during training, this may not only support skill acquisition but also increase self-confidence. Note that questionnaires such as the SIQ more or less examine athletes' spontaneous imagery behavior and their attributions regarding the effectiveness of this behavior. Such attributions may depend on the athletes' beliefs about the underlying mechanisms. Therefore, it is no surprise that a wide range of athletes prefer the motivational functions of imagery in sports (Hall et al. 1998). The corresponding knowledge about motivational effects is strongly grounded in common folk psychology. Athletes on all levels learn to "think positive" and to imagine their own success prior to trials in training and
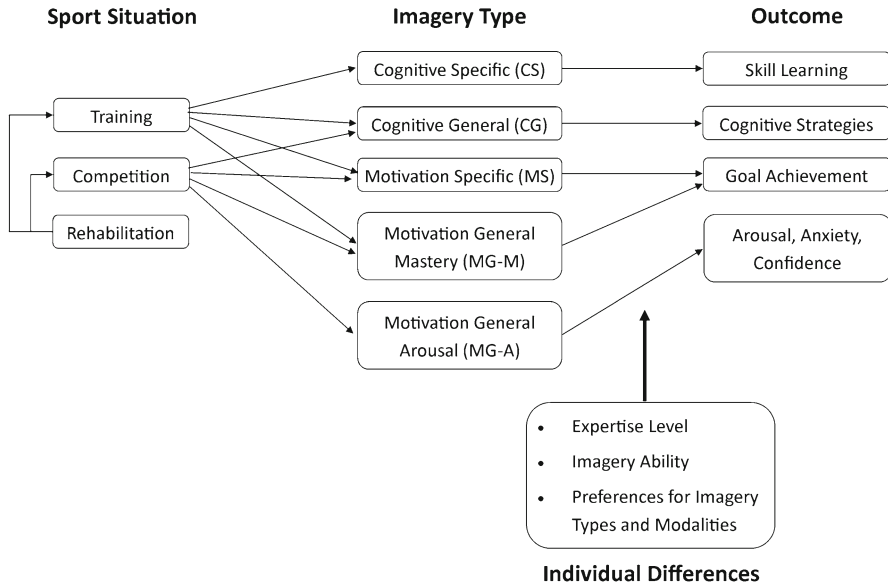
Fig. 17.1 An applied model of imagery use. The model depicts assumed relations between individual and external factors (modified and extended from Martin et al. 1999). *Note*: Rehabilitation is linked with training and competition. This represents the finding that the frequency of using motivational and cognitive components of imagery correlates with their use before injury (Sordoni et al. 2000) (cf. Sect. 17.3.1)

competition. Indeed, the rowing study by Barr and Hall (1992) revealed that winning the race was imagined much more frequently than losing it. This does not mean that the relation between imagery type and performance is not effective, but it does mean that different outcomes of imagery should be examined in detail.

During the last 10 years, the SIQ has been used to study imagery use for different imagery functions in several sports. Whereas most of these studies have assessed different expertise levels, a few have compared athletes from different sports. For example, Watt et al. (2008) assessed 484 individuals who practiced a wide range of sports. They found that in general, individuals used MG-M most, followed by CS and CG. There were only a few significant differences between expertise levels. The frequency of CS was significantly higher in athletes competing on a national level compared with those engaging in recreational sport. MG-A was reported to be significantly higher in district- compared with state- and national-level athletes. The authors classified each of the 54 sports into either open or closed skills. A higher MS level was found for open skills with perceptual-motor affordances compared with closed skills. There were no other significant differences with respect to task categorization.

Hallman and Munroe-Chandler (2009) examined imagery use and imagery abilities in a sample of 258 competitive male ice hockey players differentiated according to their playing position (goalkeepers, defense, forwards). This distinction offers a fine opportunity to study functional relations between task requirements and imagery use within

the same sport. Goalkeepers in particular need to react to anticipatory cues very quickly. The SIQ data showed more extensive use of CS and MG-M imagery in goalkeepers compared with field players, whereas no significant differences were found for other functions and no significant differences between defense players and offense players. Goalkeepers also revealed more vivid visual imagery from a first- than from a third-person perspective, whereas no significant differences were found between defense and forwards, and no significant differences were found for kinesthetic imagery.

Nordin and Cumming (2006) developed their Dance Imagery Questionnaire (DIQ) in three successive studies with more than 1,000 participants. Three of its subscales are very similar to the CS/CG, MG-M, and MG-S of the SIQ. A fourth subscale includes items representing expression, harmony between the movement and the music, and metaphors. This subscale contains an explicit aesthetic component of movement imagery. The DIQ was administered to 268 individuals practicing in either dance or aesthetic sports, such as figure skating and equestrian vaulting (Nordin and Cumming 2008). Compared with athletes, dancers reported more imagery concerning technique, goal, and aesthetic movement qualities, with imagery of techniques being more frequent than any of the other categories. Athletes likewise reported more frequent imagery for technique compared with aesthetic movement qualities. These studies increase the scope of imagery types and functions by introducing aesthetic components of imagery. Hausenblas et al. (1999) introduced a similar enlargement of the classification of dimensions of imagery use to examine imagery use in aerobics. They also studied cognitive and motivational aspects but found three basic dimensions of imagery use addressing energy, appearance, and technique. In summary, the studies reported in this section show that imagery use in sports depends on the task and the individual's expertise level and that it correlates with the athletes' belief about functions of mental imagery.

A distinctly different approach examines the impact of imagery on rehabilitation and healing. Sordoni et al. (2000) adapted items of the SIQ to injury rehabilitation situations. They applied the Athletic Injury Imagery Questionnaire to 71 injured athletes who had attended a minimum of five physiotherapy treatments. Previously, the athletes had competed in 19 different sports at different expertise levels. Injured athletes used less imagery during rehabilitation compared with healthy athletes whose data were cited in classical SIQ studies. Starting at a lower baseline, they used more motivational than cognitive components of imagery. This pattern is similar to healthy athletes. An interesting finding is that the frequency of using motivational and cognitive components of imagery correlated strongly with their use before injury. Thus injury did not influence the use of imagery except to reduce it in general. This demonstrates that imagery use is closely linked to a personal style of mental practice. Driediger et al. (2006) conducted in-depth interviews with ten injured athletes. These athletes reported imagery use for all SIQ categories. They used CS to improve specific rehabilitation exercises: MG-A, for stress reduction; MG-M, to enhance self-confidence; and MS, to enhance the achievement for future exercise sessions. They reported no imagery use relying on CG. Alongside the classical SIQ categories, additional imagery functions for healing and pain reduction were most prominent.

17.3.2   Imagery in Motor Skill Acquisition

We shall start by reviewing the basic assumptions about the influence of mental practice on skill acquisition in an examination of several meta-analyses conducted over the past 25 years. We shall then discuss specific experiments indicating which parameters exert an important influence on the processing of imagery. The perspective will be extended to skill acquisition outside the sports domain. Finally, this section reports the evidence on how imagery enhances strength gains.

17.3.2.1   Why Does Mental Practice Work? Has It Been Confirmed in Meta-analyses?

Two different meta-analyses with an overlapping body of studies were conducted during the 1980s and 1990s to examine the effectiveness of mental practice in the motor and sports domain. Feltz and Landers (1983) started their analysis with 60 studies reporting 146 effect sizes. Driskell et al. (1994) calculated their meta-analysis on the basis of 35 studies reporting 100 separate effect sizes. Both meta-analyses reported small to moderate overall effects for mental practice (0.5 standard deviations). Driskell et al. (1994) reported a fail-safe number of $N = 4,129$. This means that it would take more than 4,000 undiscovered studies that failed to find any effect of mental practice to reduce the significant overall effect at $p < 0.05$.

Do these overall results of both meta-analyses confirm a significant impact of mental practice on skill acquisition? In terms of statistical significance, we clearly have to draw a positive conclusion: The literature reports more positive than negative effects of mental practice. Additionally, the high fail-safe number indicates a robust effect. On the other hand, the effect size is only moderate, and its value depends largely on the type of skill to be learned. Therefore, it is necessary to identify which basic factors predict positive effects of mental practice with a high level of certainty. Because most studies have found stronger enhancement for active practice compared with mental practice (Driskell et al. 1994; Feltz and Landers 1983), nobody has suggested replacing active training trials by mental training trials. Instead, mental training is used as an extra tool for performance enhancement. Especially in top-level sports, small gains are helpful and desired.

Both meta-analyses differentiated the tasks to which mental practice was applied. They each state that the effect size of mental practice improves the more a task includes cognitive requirements (foremost perceptual and symbolic task elements). Mental practice is less effective for tasks involving coordination or strength requirements (but see further below). Maze learning is an example of a predominantly cognitive task. The learning process is not based on learning to coordinate a finger movement, but on learning a combination of finger movements in order to execute the shortest trajectory in experimental tasks. The task requirements relate to those found in problem-solving tasks. In sports, similar task requirements result from learning paths, for example, fast breaks in basketball and other team sports.

The bias in favor of more cognitive tasks may be a result of the relatively short training durations in most experimental studies. Such privileged cognitive tasks rely on a rapid learning progress compared with core motor tasks. Therefore, the duration of training is a critical factor (cf. Driskell et al. 1994) that may well account for task differences. This leads to the obvious conclusion that different learning mechanisms are involved during the mental practice of cognitive versus motor tasks. Heuer (1985) discussed two different approaches to explain learning effects following mental practice: the cognitive hypothesis and the programming hypothesis. These are not seen as exclusive concepts but more as complementary concepts. Here, we would add the notion that these complementary mechanisms work on different timescales.

There has been some discussion as to whether the effect of mental practice depends on expertise. Feltz and Landers (1983) found higher effect sizes for experts than for novices, though the difference was not statistically significant. Driskell et al. (1994) reported higher effect sizes for novices than for experts, though this difference also failed to attain significance. Their results revealed an additional difference between experts and novices concerning the task type. Novices showed stronger effects of mental practice for cognitive compared with motor tasks. In contrast, experienced subjects did not show the same difference. They benefited from mental training for both types of task. This may be interpreted as indicating that novices benefit from symbolic learning processes that are relevant for cognitive tasks. Experts may also retrieve motor programs effectively during mental practice and benefit from this learning mechanism—especially for motor tasks.

17.3.2.2 Specific Evidence from Learning Experiments

Despite a rich body of studies revealing a moderate effect of mental practice in sports, no model of mental training exists that could be applied to all sports. Fairly recently, Holmes and Collins (2001) introduced an applied approach to sports based on the concept of functional equivalence between action and motor imagery. It can be used as a practical guideline for decisions on how to implement mental rehearsal techniques. A few studies have successfully implemented mental training techniques on this basis for field hockey penalty flicks and gymnastics (Smith et al. 2007) and golf bunker shot performance (Smith et al. 2008).

Sport science has critically examined the outcome of different imagery perspectives. It has been hypothesized that first- and third-person visual imagery have a differential influence on skill acquisition depending on the type of motor skill. White and Hardy (1995) investigated this notion with one task in which the form of the movement was important (gymnastic-like movements) and a second task in which participants had to learn a slalom-like course. The results did not just reveal a differential influence of imagery perspectives on skills with different task requirements. They also revealed a differential influence on different learning parameters within the same skill. Participants using a (visual) third-person perspective were significantly faster than those using a first-person perspective.

On the other hand, the group utilizing first-person perspective showed fewer errors when completing the course. Contrary to assumptions in the literature (Mahoney and Avener 1977), White and Hardy (1995) found an advantage of the third-person perspective when participants had to memorize body positions in the gymnastic-like movements. They interpreted this result as an indication that the third-person perspective affects the learning process of the gross form of a movement. As a side effect, they reported data indicating that both visual perspectives evoke kinesthetic imagery with the same frequency. These results resemble data found for badminton techniques (Munzert et al. 2000).

Hardy and Callow (1999) performed a detailed examination of the effect of imagery perspectives in tasks during which form is important. When karate experts had to learn a new kata, i.e., a complex sequence of movements without an opponent, a third-person perspective proved to be more successful than a first-person perspective. In a second experiment, first- and third-person perspectives were combined with or without kinesthetic imagery while sport students were learning simple floor routines. Again, there was a significant advantage for the third- compared with the first-person perspective. No significant effect was found for kinesthetic imagery. When Hardy and Callow (1999) transferred the design of this second experiment to expert rock climbers, they found the same advantage for third-person perspective and a further advantage for kinesthetic imagery. The results of these three experiments strongly support the assumption that a third-person perspective is most effective for skill acquisition in tasks that depend on the realization of the underlying movement for their successful performance (Hardy and Callow 1999).

In sports training, athletes often practice routines that are different to the skills used in actual competition. How to transfer these training routines to competition performance is a well-known problem. It is therefore interesting to ask whether mental practice can enhance this transfer. One study by Van Gyn et al. (1990) examined this question. Participants completed a 6-week peak power training using a cycle ergometer with the aim of improving sprint time. The design contained four groups: peak power training alone, peak power training in conjunction with mental imagery of their sprint performance, mental imagery alone, or controls. When testing peak power on the cycle ergometer, the groups with active training and with active training in conjunction with imagery showed significant improvement. In contrast, only the group with the combination of peak power training and mental imagery revealed a significant enhancement of 40-m sprint time. These results indicate that mental imagery might support the transfer from training to competition—at least under certain conditions. However, not much is known about this effect of mental practice to date.

17.3.2.3 Evidence from Outside the Sports Domain

In this passage, we shall discuss why findings of the effects of mental imagery on motor skill acquisition outside the traditional sports domain are relevant for visual and motor imagery. An analysis of surgical practice reveals requirements similar

to some specific but not all sports conditions (see also Chap. 18). A closer look at studies on the effects of mentally rehearsing surgical skills reveals that many requirements in this field are based on a complicated relation between visual and motor output conditions. For example, the visual–motor relation seems to be critical in laparoscopy. This relation is also relevant in diving or in sports when motor skills have to be produced under difficult visual conditions. In general, there are many conditions in sports such as serves in tennis and badminton, or penalty kicks in soccer, in which specific visual conditions have an effect on motor control. This relation may be more questionable for playing musical instruments. But is this really different from some sports? Playing instruments at a high level requires outstanding fine-motor skills. One difference may be that motor skills in sports are often more gross, but similar fine-motor skills are used in sports such as snooker, darts, or cricket. Mental practice has also been used to enhance skill acquisition in music performance. Two studies, one on the acquisition of trombone skills (Ross 1985) and one on piano playing (Coffman 1990), both underline a benefit in learning due to a combination of physical practice and mental practice. However, because the number of participants in training conditions was quite small, these results have to be interpreted with caution. Nonetheless, learning to play an instrument is an interesting field in which mental imagery may well be applied more often in the future.

17.3.2.4   Mental Practice and Strength Gains

Significant strength gain effects after mental practice have been reported repeatedly since the pioneering experiments of Yue and Cole (1992). In their study, participants completed a 4-week isometric force production training of the little finger either physically or mentally. Both groups showed similar strength gains: 29.8% for the physical training group and 22% for the mental training group. Additionally, both groups differed significantly from a control group that exhibited only a very small gain of 3.7%. Alongside the strength gain in the mental training condition, there was also a considerable strength gain on the contralateral side that was not trained (physically or mentally). This nicely demonstrates that early strength gains are due to neural effects and that these neural effects can be enhanced by mental training. There are two sources, central neural processes or peripheral processes, which contribute to strength gains on a muscular level. If subjects do not exercise physically strength gains relying on processes on the muscular level can be excluded explicitly. The same argument holds for the contralateral transfer. This effect reflects likely changes in motoneuron output as opposed to changes in the muscular structure of the contralateral limb (Carroll et al. 2006).

Reiser (2005) conducted a study with a typical sport task requiring bilateral isometric bench pressing. He found a strength gain of about 5.7% for mental training of bench pressing. Although this was a smaller effect than that found in earlier studies, it still represents a significant increase. Most studies reporting effects of mental practice on strength gains compared groups that trained either only physically or

only mentally (cf. Reiser et al. 2011). The experimental design made it possible to demonstrate that mental practice produces a verifiable increase in strength. In more practical situations, however, this is not the alternative that needs to be examined. It may be needed only when mental training is used to reduce strength losses occurring after immobilization of a limb (Mulder et al. 2006). The practical question is whether some physical training can be replaced by mental training. Reiser et al. (2011) examined three groups with different combinations of physical and mental training (75, 50, 25, and 0% mental trials during training) for exercises such as bench pressing, leg pressing, triceps extension, and calf raising. Mental training groups showed only slightly smaller strength increases than the group that exercised only physically. These training effects remained stable after 1 week without training. The results demonstrate that physical strength training sessions can be partly replaced by mental training sessions without any significant reduction in strength.

17.4 Imagery and Self-Efficacy, Confidence, and Anxiety

Alongside optimizing motor performance, supporting motor rehabilitation processes, or refining motor skills (Driskell et al. 1994; Feltz and Landers 1983; Feltz et al. 1988; Mulder 2007), mental imagery is also used to enhance athletes' motivational and emotional processes (Hall et al. 1990; Martin et al. 1999; Munroe et al. 1998, 2000). This is particularly important in elite sport, because athletes have to perform under demands that can be characterized as high-pressure situations. Several studies (Barr and Hall 1992; Hall et al. 1990) have shown that athletes across all competitive levels use imagery extensively but that athletes at higher competitive levels report using more imagery involving both visual and kinesthetic aspects. Athletes use imagery during actual competitions, before or after practice, or outside of practice and competition (Weinberg et al. 2003). Barr and Hall (1992) and Rodgers et al. (1991) found that imagery was employed most often before a competition. For example, Salmon et al. (1994) found that soccer players use imagery more for its motivational function than for its cognitive function when preparing themselves for both training practice and competition. Weinberg et al. (2003) also reported that imagery was utilized most often by athletes in difficult situations when they were under increased pressure. They also often used imagery when they were competing less successfully and when they were injured or tired.

As described above, Paivio's (1985) attempt to systematize functions of imagery use in sports describes not only cognitive functions but also two motivational functions of mental practice. The Motivation-Specific factor refers to the use of imagery to enhance a specific goal attainment such as imagining oneself winning an event, standing on the podium, and receiving a medal. In contrast, the Motivation-General factor refers to the general function of images on physiological and emotional arousal including techniques for relaxing or for increasing arousal. The main aims here are to regulate self-confidence, to master anxiety, and to enhance mental toughness.

Research focusing on the MG factor of imagery utilization has revealed that many athletes use imagery as an important psychological skill. Looking at the motivational and emotion-regulative aspects of imagery use, confidence and anxiety management seem to be particularly important characteristics for athletes (Vealey 1986). For example, imagery usage is associated positively with attributes such as sport confidence (Callow et al. 1998; White and Hardy 1998). Furthermore, imagery has been proposed as an effective strategy for controlling the level of anxiety (Vadocz et al. 1997). The following two sections discuss both aspects and the usefulness of imagery strategies in more detail.

17.4.1   Imagery Use, Confidence, and Self-Efficacy

One interesting relationship between imagery use and confidence was reported by Abma et al. (2002). They examined how "high-trait sport-confident" versus "low-trait sport-confident" track and field athletes differed in their imagery content and imagery ability. Their data revealed that high-confident athletes utilized all types of imagery more than low-confident athletes but did not reveal more pronounced imagery skills than low-confident athletes. The fact that high-confident athletes utilize significantly more imagery than low-confident athletes indicates the importance of mental skills training, especially when noting that high-confident athletes performed at a higher level than low-confident athletes. Within this framework, Martin et al. (1999) argued that particular types of imagery, like MG-M imagery, are optimal for enhancing confidence levels in athletes. However, they suggested that athletes also use other types of imagery with the aim of enhancing their confidence level.

To further elucidate the relationship between imagery type and confidence, Callow and Hardy (2001) asked 123 female county netball players to complete the SIQ and then 1 week later the State Sport Confidence Inventory (SSCI) at a netball county match. Their results demonstrated that mastery imagery and imagery relating to game strategy accounted for a significant proportion of the variance in sport confidence. Furthermore, imagery related to emotions predicted the confidence level negatively. Specifically, confidence increased as imagery of negative emotions decreased. Finally, among higher class athletes, goal achievement imagery was the only predictor of their sport confidence level.

Another sport-confidence-related trait is an athlete's self-efficacy. Self-efficacy is a term roughly corresponding to a belief in one's own competence (Bandura 1977). Beauchamp et al. (2002) examined the relationship between athletes' self-efficacy, precompetition imagery use, and performance. A total of 51 golfers completed a modified version of the SIQ during the hour before a provincial university golf championship. Results revealed that MG-M imagery accounted for significant variance in self-efficacy and performance. Furthermore, this study demonstrated that self-efficacy predicted golf performance and that MG-M imagery use mediated the relationship between self-efficacy and performance. An earlier experiment by Feltz and Riessinger (1990) tried to elucidate

the merits of in vivo emotive imagery and performance feedback by enhancing self-efficacy beliefs and performance on a competitive muscular endurance task. They examined 120 undergraduates in three conditions: mastery imagery plus feedback, feedback alone, or control condition. Subjects were unknowingly paired with a confederate. Pairs in the imagery-plus-feedback condition were told that one person (always the subject) would receive imagery exposure while the other (always the confederate) would wait outside. Then subjects completed two trials against the confederate always resulting in the confederate winning by 10 s. Results show a significant increase in confidence for the imagery group after brief exposure to imagery. Participants assigned to the imagery and feedback condition had significantly higher self-efficacy scores than participants assigned to feedback alone or the control condition. Interestingly, performance feedback alone did not influence efficacy beliefs or performance.

In sum, it can be concluded that sport confidence and self-efficacy are associated with the usage of imagery strategies and that different forms of imagery influence the confidence level. However, the results also demonstrate that different people probably benefit from different kinds of imagery; that is, one athlete might prefer image strategies for play or competition, whereas another athlete might prefer to imagine motivational scenes to enhance confidence (for example, Callow and Hardy 2001). From an applied perspective, coaches must be aware of the different types of imagery so that the types of imagery they recommend help the individual athlete.

17.4.2   Imagery Use and the Regulation of Anxiety

Because elite athletes face a high demand to perform at optimal levels in high-pressure situations, much attention has been directed toward efficient and successful coping strategies in stressful situations (Jones 1991). Coping with different forms of anxiety is particularly important. Anxiety is often defined here as "one's perception of the physiological-anxiety experience, that is, indications of autonomic arousal and unpleasant feeling states such as nervousness and tension" (Morris et al. 1981, p. 541). The cognitive component of anxiety includes negative expectations and concerns about oneself, the situation, and possible consequences (Morris et al. 1981).

The use of mental imagery has been proposed as a prominent strategy to control stress and anxiety in sports (Salmon et al. 1994). Several studies have tried to elucidate the effects of imagery on anxiety. Vadocz et al. (1997) examined competitive anxiety, and their results suggested that imagery can be used to control competitive anxiety levels and enhance self-confidence. More precisely, they found a relationship between visual imagery ability, motivational arousal, and anxiety. Monsma and Overby (2004) examined a specific form of state anxiety in sports that is related to choking under pressure during a public audition. They explored the role of imagery concerning the anxiety–performance relation in 131 ballet dancers. They assessed competitive state anxiety and confidence as well as

cognitive and motivational functions of imagery and also movement imagery abilities. Results showed that successful dancers with prior positive experience with auditions were more confident than those without prior positive experience. Furthermore, successful dancers experienced less cognitive anxiety and more somatic anxiety than unsuccessful dancers. Although imagery ability and image content did not differentiate between dancers in terms of performance, confident dancers revealed higher kinesthetic imagery ability and used more mastery and less arousal imagery than less confident dancers. In contrast, cognitively and somatically anxious dancers used less mastery imagery and more arousal imagery. Hence, these data suggest that dancers should be encouraged to focus on mastery images in order to increase confidence and reduce anxiety.

Of special interest for athletes and also for patients might be the use of motivational imagery strategies during the rehabilitation process after injury. It is known that kinesthetic imagery does support the rehabilitation process at the motor level (see for a review, Mulder 2007). However, it would be interesting to know whether imagery strategies might influence the motivational and emotional state of the injured athlete. Cupal and Brewer (2001) investigated the effects of relaxation and guided imagery on knee strength, reinjury anxiety, and pain in surgery patients. They suggested that relaxation and imagery might well support the rehabilitation process by showing that ten relaxation and guided imagery sessions resulted in superior knee strength and less reinjury anxiety and pain for the treatment group at 24 weeks post surgery than for placebo and control groups. These results indicate the possibility of influencing emotional and motivational qualities of the athlete or the patient during the rehabilitation process.

In conclusion, motivational imagery might be an appropriate tool for countering different forms of anxiety prior to a performance or a competitive situation and also during rehabilitation processes—perhaps because it enables athletes to "psyche themselves up" to compete and feel more confident.

17.5 Conclusions

In general, visual and motor imagery may serve different purposes in sports and specifically in top-level sports. On a first level, effects on motivational and skill learning can be differentiated. Traditional research on motor skill learning has emphasized the functions of cognitive- and information-relevant processes. As pointed out above, there is ample evidence that different forms of imagery including different imagery modalities and perspectives contribute to motor learning. On the other hand, evidence about the motivational and emotional consequences of visual or motor imagery for actual performance is rather weak. It is based on correlational studies that often do not allow a causal interpretation of the data. This is not necessarily a negative conclusion, but a call for more serious experimental evidence about the motivational and emotional functions of imagery in sports. Future research will examine skill-related and motivation-oriented functions of imagery as well as their interdependence.

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Chapter 18
Mental Imagery and Mental Practice Applications in Surgery: State of the Art and Future Directions

Nick Sevdalis, Aidan Moran, and Sonal Arora

Abstract This chapter aims to provide a state-of-the-art review of the application of mental imagery and mental practice (or motor imagery) within surgical contexts. We first explain the terms "mental imagery" (a form of cognitive simulation) and "mental practice" (or the covert rehearsal of an action in one's imagination without executing the actual movements involved) and summarise the main theories of mental practice effects. We then propose some important similarities between the skilled performance of surgeons and that of elite athletes, and we review the current status of surgical training—highlighting the growing popularity of simulation methods as a cost-effective alternative to the traditional apprenticeship model whereby novice surgeons hone their skills through repeated supervised experience of operating. Next, we review available empirical research on the efficacy of mental practice interventions in training surgical skills—with special emphasis on the key methodological issues afflicting research in this field. Finally, we present our conclusions and identify some fruitful avenues for further research on mental practice in surgery and surgical training.

Keywords Mental practice • Mental imagery • Mental rehearsal • Surgery • Surgical education • Operating room • Operating theatre

N. Sevdalis, B.Sc., M.Sc., Ph.D. (✉) • S. Arora, B.Sc., M.B.B.S., M.R.C.S., Ph.D.
Department of Surgery and Cancer, Imperial College London,
St Mary's Hospital Campus, Wright Fleming Wing (room 507),
Norfolk Place, London, W2 1PG, UK
e-mail: n.sevdalis@imperial.ac.uk

A. Moran, B.A., M.A., Ph.D., F.B.Ps.S.I., A.F.B.Ps., C.
School of Psychology, University College Dublin,
Dublin, Ireland

18.1   Introduction

One of the most remarkable capacities of the mind is its ability to simulate sensations, actions and other types of experience. As Crisp et al. (2011) proclaimed recently, "the ability to envisage a world different from that which we know is one of the defining characteristics of human experience" (p. 261). For over a century, researchers have investigated *mental imagery* or the cognitive simulation process by which we can represent perceptual information in our minds in the absence of appropriate sensory input (Munzert et al. 2009). More recently, however, a mental simulation process that has attracted increasing attention from cognitive neuroscientists and sport psychologists is "motor imagery" (traditionally known as "mental practice") or the mental rehearsal of actions without engaging in the actual physical movements involved (see recent review by Moran et al. 2012). Research on motor imagery is important not only because it provides an empirical window on movement planning but also because, through its application in mental practice (explained later), it can facilitate skill learning and skilled performance in athletes (Moran and MacIntyre 1998; Weinberg 2008) and surgeons (Arora et al. 2010, 2011a, b). Given the theoretical and practical importance of mental simulation processes, this chapter explores the role of mental imagery and mental practice in surgical training and performance.

18.1.1   *Mental Imagery: Nature and Characteristics*

According to cognitive researchers, mental imagery has three key characteristics—it occurs in all sensory modalities (a key theme of this book), is classifiable into different types and shares certain neural substrates and cognitive mechanisms with other mental processes. These characteristics may be explained briefly as follows.

To begin with, mental imagery is a multi-modality construct (see also Chap. 9). As Hardyet al. (1996) explained, it is "a symbolic sensory experience that may occur in any sensory mode" (p. 28). Thus we have the capacity to imagine "seeing", "hearing", "tasting", "smelling" and "feeling" simulated actions and experiences. As imagery is multi-sensory in nature, different *types* of mental imagery have been identified. For example, cognitive neuroscientists distinguish between two kinds of visual imagery (see Chaps. 14 and 16). The second notable feature of mental imagery is that although it is unobservable, it is measurable indirectly through individual variations in such dimensions as "vividness" (i.e. apparent realism, clarity or richness) and "controllability" (i.e. the ease with which a given mental image can be manipulated by the person who generates it) (Moran 1993). Over the past century, these dimensions of imagery have been targeted by psychologists in their attempt to measure individual differences in people's use of and ability in imagery (see Chap. 14; Morris et al. 2005). For example, the vividness of an image can be assessed using self-report scales in which people are asked to comment on certain experiential aspects of their imagery representation. The third important aspect of mental imag-

ery concerns its neurological substrates. Specifically, research shows that visual and motor imagery share some neural pathways and mechanisms with like-modality perception (Farah 1984; Kosslyn 1994) and also with the preparation and production of movements (Decety and Ingvar 1990; Jeannerod 1994, 2001), respectively. In short, there are close parallels between perceiving, imagining and motor control (planning and executing actions). Recognition of these parallels led to the "functional equivalence" hypothesis (e.g. Finke 1979; Jeannerod 1994; see review by Moran et al. 2012) or the proposition that cognitive simulation processes (e.g. imagery) share, to some degree, certain representations, neural structures and mechanisms with like-modality perception and with motor preparation and execution processes. Having briefly sketched the nature, types and measurement of imagery, let us now consider research on mental practice (MP).

18.1.2   Mental Practice

The term "mental practice" (also known as "symbolic rehearsal" or "covert rehearsal") refers to the systematic use of mental imagery to "see" and "feel" an action in one's imagination without engaging in the actual physical movements involved. For over a century, the effects of MP on skilled performance have been investigated by researchers in psychology. For example, James (1890) claimed rather counter-intuitively that by anticipating experiences imaginatively, people actually learn to skate in the summer and to swim in the winter. The typical experimental paradigm used to study MP effects involves a comparison of the pre- and post-intervention performance of four groups of participants: those who have been engaged only in physical practice of the skill in question (the physical practice group, PP); those who have mentally practised it (the mental practice group, MP); those who have alternated between physical and mental practice (PP/MP) and, finally, participants in a non-practice control condition. After a pretreatment baseline test has been conducted on a designated skill, participants are randomly assigned to one of these conditions (PP, MP, PP/MP or control). Normally, the cognitive rehearsal that occurs in the MP treatment condition is guided by a mental imagery "script" that describes the motor actions to be executed in clear and vivid detail (see Morris et al. 2005). After this MP intervention has been applied, the participants' performance on the target skill is tested again. If the performance of the MP group is significantly superior to that of the control group, then a positive effect of mental practice is deemed to have occurred.

Using the preceding experimental paradigm, imagery researchers have established a number of conclusions about the efficacy of mental practice (see reviews by Driskell et al. 1994; Schuster et al. 2011). First, MP has been shown to improve the learning and performance of a variety of motor skills in sport. These skills include self-paced activities such as golf-putting (Bell et al. 2009; Ramsey et al. 2008) and the high-jump (Olsson et al. 2008) as well as open skills such as the service return in tennis (Robin et al. 2007). Mental practice interventions

have also been applied successfully to enhance performance in music (Gregg and Clark 2007), dance (Bolles and Chatfield 2009) and surgery (Arora et al. 2010, 2011a, b). Second, there is evidence (see Driskell et al. 1994) that MP, when combined and alternated with physical practice, tends to produce superior skill-learning to that resulting from either mental or physical practice conducted alone. Interestingly, this principle has been investigated in stroke rehabilitation. Thus mental practice combined with physical practice yields better outcomes in movement recovery than does physical practice alone (Malouin et al. 2009; Page et al. 2007). Third, although an early review by Feltz and Landers (1983) concluded that mental practice is more effective for the improvement of cognitive rather than motor components of sport skills, there is research evidence that MP can increase physical strength performance (Smith et al. 2003; Reiser et al. 2011). Fourth, Driskell et al. (1994) concluded that expert athletes tend to benefit more from MP than do novices, regardless of the type of skill being practised (either cognitive or physical). Support for this claim comes from research (e.g. Arvinen-Barrow et al. 2007) on the benefits of imagery for highly skilled performers. To summarise, a wealth of studies indicate that mental practice can enhance skill-learning and skilled performance in athletes.

Despite an abundance of research on the efficacy of MP, there is at least one unresolved question—a validation issue—that afflicts this field. Specifically, how do we know that people who claim to be using imagery when engaged in mental practice are actually doing so? The most popular way of addressing this issue is to use custom-designed manipulation checks or verification procedures that attempt to assess the ease and accuracy with which participants adhered to the imagery instructions/script that they had received (Cumming and Ramsey 2009).

18.1.3 Theories of Mental Practice

In general, three main theories have been postulated to explain MP effects—the "neuromuscular" model (e.g. Jacobson 1932), the cognitive or symbolic approach (e.g. Denis 1985) and the "bio-informational" theory (e.g. Lang 1979). These theories may be summarised briefly as follows (Moran 2012).

To begin with, the neuromuscular model proposes that mental practice effects are mediated by faint activity in the peripheral musculature. This theory postulates that there is a strong positive relationship between the muscular activity elicited by imagining a given skill and that detected during actual execution of this skill. Unfortunately, empirical support for this hypothesis and, more generally, for neuromuscular theories of mental practice is inconsistent. For example, whereas Guillot et al. (2007) discovered electromyographic (EMG) activity during motor imagery, Gentili et al. (2006) failed to do so (see also Chap. 6).

Next, the cognitive approach suggests that mental practice facilitates the coding and rehearsal of key elements of the skilled task. By contrast with neuromuscular accounts of MP, cognitive (or symbolic learning) models attach little

importance to what happens in the peripheral musculature of the performer. Instead, they focus on the possibility that mental rehearsal strengthens the brain's central representation or cognitive "blueprint" of the skill being imagined (Roosink and Zijdewind 2010). Although this approach has a plausible theoretical rationale, it is challenged by evidence that MP can improve people's performance of strength tasks which, by definition, contain few cognitive components. Another problem for symbolic theories is that they find it difficult to explain how MP can enhance the performance of expert athletes who, presumably, already possess well-established blueprints or motor schemata for the movements being imagined.

Finally, the bio-informational theory postulates that MP effects reflect an interaction of three different factors: the environment in which a given movement is performed ("stimulus" information such as "feeling" the soft ground as one imagines teeing up a ball in golf), what is felt by the performer while the movement occurs ("response" information such as feeling a slow, smooth practice swing on the imaginary tee-box) and the perceived importance of this skill to the performer ("meaning" information such as feeling slightly anxious because other people are watching as one prepares to drive the ball). Of these factors, the response propositions are held to be especially significant because they are believed to reflect how a person would actually react in the real-life situation being imagined. Therefore, bio-informational theorists postulate that imagery scripts that are heavily laden with response propositions should elicit greater MP effects than those without such information.

18.2   Similarities Between Surgical and Sporting Skills

In many ways, surgical performance is similar to competitive sports performance: both require intense concentration, complex fine and gross motor ability, and both are routinely performed in dynamic environments characterised by considerable pressure (Rogers 2006). Indeed, many surgeons anecdotally report using their own intuitive and informal imagery strategies, by going over the procedure in their mind before actually operating (Sanders et al. 2004). Given these parallels between surgery and sports performance, it seems plausible that MP could be useful for reducing stress and enhancing performance in surgeons. As MP is a form of cognitive simulation, it may also be beneficial as a psychological strategy to augment the traditional approach to surgical training that is outlined below (Goff 2008; McCaskie et al. 2011; Pugh 2012).

18.3   Current Status of Surgical Training

The fundamental aim of surgical training is to produce the most competent surgeon possible (Youngson et al. 2010). Quite how this training should take place, however, is one of the most hotly debated topics currently engaging the profession (De Cossart

and Fish 2005). Although it is beyond the scope of this chapter to provide a detailed review of the development of, and issues affecting, surgical training (but see Department of Health 2003; Donaldson 2002; Tooke 2008), some general trends may be summarised as follows.

Traditionally, surgical training has been conducted using the "see one, do one, teach one" approach—an apprenticeship model whereby novice surgeons learned their craft through repeated supervised practice (involving 15,000–20,000 h; McCaskie et al. 2011) on patients in an operating room.

Unfortunately, as has been well documented (e.g. see Moulton et al. 2006; Tooke 2008), this apprenticeship model of surgical training is plagued by theoretical and practical difficulties. For example, at a theoretical level, there is growing evidence that the OR is not an ideal learning environment for the training of surgical skills (Kneebone et al. 2005, 2007). Specifically, this environment is not learner centred because, for ethical reasons, the main priority must always be the patient's safety rather than the quality of learning experienced by the trainee surgeon. At a practical level, due to service demands (e.g. an increasing emphasis on OR efficiency), time pressures (e.g. shorter working weeks) and other stressors, expert surgeons may not be able to impart their knowledge and skills to their juniors in a cost-efficient manner (Arora et al. 2009; Grantcharov and Reznick 2009; Grantcharov et al. 2004).

Against this background of pedagogical and practical challenges, an alternative model of surgical training has evolved based on surgical simulation (e.g. see Kneebone and Aggarwal 2009; McCaskie et al. 2011), in which new technologies (i.e. virtual reality simulators) are used to mimic the surgical environment in all relevant respects. A key advantage of surgical simulation technology (e.g. see Fig. 18.1) is that it enables trainees to practise their skills in a realistic environment without any risk to patient safety.

However, these technological advances have posed significant challenges to surgeons at all levels of training (Calatayud et al. 2010). Such challenges include those of learning to use a two-dimensional screen in order to judge a complex and dynamic three-dimensional scene and of mastering surgical technology that is often counter-intuitive in design (Aggarwal et al. 2006; Grantcharov et al. 2004). Not surprisingly therefore, these techniques have a steep learning curve which surgeons must overcome (Aggarwal et al. 2006). Given such problems, some researchers have begun to explore the potential of mental simulation techniques for the enhancement of surgical training and performance (e.g. Arora et al. 2010). So, in the next section of this chapter, we shall explore the available evidence on how mental imagery and MP have been used as an alternative approach to train surgeons and enhance their operative performance.
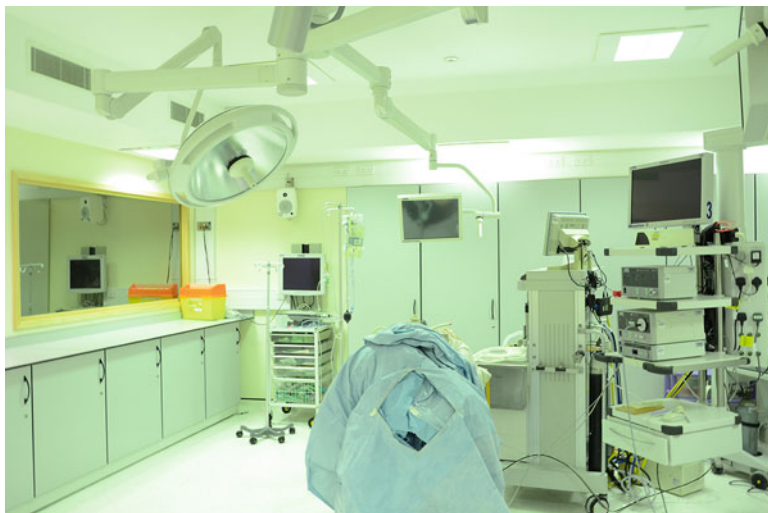
Fig. 18.1 Simulated operating room environment

18.4 Research on Mental Imagery and Mental Practice in Surgical Contexts: Search Strategy, Methodological Issues and Key Findings

18.4.1 Search Strategy and Characteristics of Retrieved Articles

Within surgery, there have been various calls to import strategies for the enhancement of surgeons' performance based on experience of other industries. Typically, surgeons have been urged to focus on developing their technical as well as their "non-technical" skills, in other words skills that enhance team performance in the OR, particularly when crises occur (Vincent et al. 2004; Yule et al. 2006); to use checklists (Haynes et al. 2009) and to use preoperative team briefings and post-operative debriefings (Lingard et al. 2008). Such interventions all originate within high-risk industries, like commercial aviation (Flin et al. 2008).

Although the aforementioned imports from the aviation and other similar industries are currently most well known within surgery, approaches based on cognitive psychology, sports sciences and the modern psychology of human performance have also been popular. Indeed, a decade ago, Hall et al. (2003) urged surgeons and surgical educators to pay more attention to surgeons' cognition—i.e. to go beyond traditional psychomotor coordination and manual dexterity. Lang (2002) explicitly called for modern surgical training to incorporate mental practice, based on the success of this approach within the sports field. In the same year, a review of the MP literature appeared in the mainstream surgical

literature (Hall 2002)—thereby providing surgeons with both the conceptual and neurological underpinnings of MP, but also its potential applications to surgical skills learning and training surgery. Recent editorials in a range of clinical journals have reiterated the same message (Goff 2008; Aoun et al. 2011; McCaskie et al. 2011; Pugh 2012), and at least one review has been published with explicit "how to" instructions regarding how best to deliver mental practice training within surgical settings (Sapien and Rogers 2010).

In order to evaluate the current state of the art of the surgical field with respect to MP research and applications, we carried out a search of the evidence base. A systematic approach to the search was undertaken: MEDLINE and PsycINFO databases were searched, via the PubMed and Ovid interfaces, respectively. The search was carried out between the earliest available entries in these databases and the third week of February 2012. Search terms included "mental practice/rehearsal/imagery/training" (including synonyms), and database hits were limited using the terms "surgery", "operating theatre/room" and "operative" (including synonyms). The reference lists of the retrieved articles were also hand-searched for relevant references, and all articles on the topic known to the authors of this chapter were also included (they were all picked up by the database searches). Retrieved articles were included in the synthesis of the evidence base if they (1) reported original research and (2) reported research on surgical tasks or performance.

The article search and data extraction were carried out by a psychologist with 8 years expertise in surgical performance research (NS) and were subsequently reviewed for accuracy and completeness of coverage by a surgeon with 5 years expertise in MP within surgery (SA) and a senior psychologist with more than 30 years expertise in the cognitive psychology of MP as well as MP applications across a range of fields (AM). No disagreements arose in this process.

Twelve different datasets were retrieved, which were reported in 13 peer-reviewed papers (Table 18.1). The earliest paper was published in 1994 and the most recent in 2011. Almost a third of the articles were published in 2011 ($n=4$), thereby revealing increased interest in MP within surgery in recent years. Eleven of the 13 articles appeared in surgical journals, with just one of them in a medical education and another one in a non-clinical publication.

Of the 13 articles, ten are experimental randomised trials with control group (Arora et al. 2011a, b; Bathalon et al. 2005; Donnon et al. 2005; Immenroth et al. 2007; Jungmann et al. 2011; Komesu et al. 2009; Sanders et al. 2004, 2008; Wetzel et al. 2011), two are qualitative studies (McDonald and Orlick 1994; McDonald et al. 1995), and one is a pre/post-intervention study without control group (Arora et al. 2010).

In the sections that follow, we critically synthesise the findings that stem from these studies with specific reference to methodological issues and the efficacy of MP in improving surgical performance.

Table 18.1 Mental practice applications in surgical contexts

Authors	Speciality and subjects	Design and methodological aspects	Key findings
Arora et al. (2010)	General surgery 10 expert vs. 10 novice surgeons	Experimental, pre/post-intervention design Mental practice protocol utilised Mental Imagery Questionnaire (*MIQ*) developed as part of the study	MP significantly improved imagery scores for novices and experts (effects were bigger in the former group)
Arora et al. (2011a)	General surgery 18 surgical novices	Experimental, randomised controlled design: control vs. mental practice groups Simulation setting Previously validated MP protocol and *MIQ*	MP subjects had significantly enhanced mental imagery and significantly better technical performance
Arora et al. (2011b)	General surgery 18 surgical novices	Experimental, randomised controlled design (2 groups of 9 subjects each): control vs. mental practice training groups Simulation setting Previously validated MP protocol and *MIQ*	MP subjects had significantly enhanced mental imagery, significantly lower subjective stress (self-reported STAI) and significantly lower objective stress (salivary cortisol, maximum heart rate)
Bathalon et al. (2005)	Ear, nose and throat 44 first year medical students	Experimental, randomised controlled design (3 groups of 13–16 subjects each): Kinesiology (based on cognitive task analysis) vs. kinesiology plus MP vs. standard ATLS instruction groups Simulation setting Ad hoc MP script (no validation evidence)	Compared to ATLS subjects, subjects in the kinesiology plus MP group had partly higher performance
Donnon et al. (2005)	Basic surgical task (laparoscopic suturing) 42 first and second year medical students	Experimental, randomised controlled design (2 groups of 20–22 subjects each): Cognitive imaging vs. control groups Simulation setting Ad hoc MP script (no validation evidence)	No significant differences

Table 18.1 (continued)

Authors	Speciality and subjects	Design and methodological aspects	Key findings
Immenroth et al. (2007)	General surgery 98 surgical novices	Experimental, randomised controlled design (3 groups of 31–35 subjects each): Control vs. practical training vs. mental practice training groups at 2 time-points: baseline vs. follow-up Simulation setting Ad hoc MP script (no validation evidence)	MP subjects improved significantly more between baseline and follow-up testing
Jungmann et al. (2011)	Basic surgical task (laparoscopic knot tying) 40 medical students	Experimental, randomised controlled design (2 groups of 20 subjects each): MP vs. control groups Simulation setting Ad hoc MP script (no validation evidence)	No significant differences
Komesu et al. (2009)	Obstetrics and Urology 64 surgical novices	Experimental, randomised controlled design (2 groups of 31–33 subjects each): Control vs. MP Real OR Ad hoc MP script (no validation evidence)	MP subjects were significantly better in parts of their technical performance (knowledge of procedure, knowledge of instruments and flow of operation)
McDonald et al. (1995); McDonald and Orlick (1994)	Various specialities 33 junior and senior surgeons	Qualitative interview study: Surgeons rated the relevance of mental vs. technical vs. physical readiness to surgical excellence	Surgeons rated "mental readiness" as highest contributor to surgical excellence, followed by technical readiness and physical readiness and recommended MP for trainees
Sanders et al. (2004)	Basic surgical task (suturing) 65 second year medical students	Experimental, randomised controlled design (3 groups of 21–22 subjects each): 3 sessions of physical practice vs. 2 sessions of physical practice plus 1 session of MP vs. 1 session of physical practice plus 2 sessions of MP Simulation setting Ad hoc MP script (no validation evidence)	No significant differences

Sanders et al. (2008)	Basic surgical task (suturing) 65 second year medical students	Experimental, randomised controlled design (2 groups of 31–32 subjects each): MP vs. textbook instruction ("cloze" passage) Simulation setting Ad hoc MP script (no validation evidence)	Compared to "textbook instruction" subjects, MP subjects had significantly better technical performance The effect was eliminated when a MP group outlier was included in analyses
Wetzel et al. (2011)	Vascular surgery 16 surgical trainees	Experimental, randomised controlled design (2 groups of 8 subjects each): Control vs. stress training (including MP) Simulation setting MP script as part of larger stress training	MP subjects had significantly more stress coping strategies

ATLS advanced trauma life support; *MIQ* Mental Imagery Questionnaire; *MP* mental practice; *STAI* State Trait Anxiety Inventory

18.4.2   Methodological Issues

Two key methodological issues become evident upon review of the available evidence: (1) design, delivery and measurement of MP interventions and (2) measurement of surgical performance.

18.4.2.1   Design, Delivery and Measurement of Mental Practice Interventions

Only two studies utilised an MP intervention that had some evidence of validity. Arora et al. (2011a, b) delivered an MP intervention to groups of surgical novices, compared their technical performance and also their stress levels with those of their control peers and found improved performance and reduced stress levels (both subjective and objective stress) in the MP groups. The intervention was previously tested extensively and shown to improve imagery quality of both novice and expert surgeons (i.e. consultant/attending level; Arora et al. 2010). Moreover, both articles report intervention delivery immediately prior to the surgical task—a methodology that is in line with current best practice recommendations (Sapien and Rogers 2010). Furthermore, in both studies a newly developed and validated survey tool was employed (Mental Imagery Questionnaire, MIQ; Arora et al. 2010), which allowed the researchers to empirically demonstrate improved surgical imagery in these studies—this is known as a "manipulation check" in the experimental psychology literature, and it allows the researcher to establish whether the MP manipulation had the intended effect prior to examining the impact of the manipulation on performance. The MIQ appears, therefore, to be the only available instrument for the assessment of the quality of mental imagery within surgical contexts (the full MIQ is depicted in Table 18.2).

    None of the other studies employed either a validated MP intervention or protocol, or a manipulation check on participants' compliance with imagery instructions. This is a key methodological problem: in the remaining studies that did find enhancement of performance following MP (Bathalon et al. 2005; Immenroth et al. 2007; Komesu et al. 2009; Wetzel et al. 2011) the findings could be used as evidence for the validity of the MP interventions. However, of these studies one mixed MP with kinesiology (Bathalon et al. 2005), one did not offer any between-subjects comparisons between the MP and the other experimental groups (Immenroth et al. 2007), and another one delivered MP within a larger stress training programme and subsequently only found more stress coping strategies in the MP-trained group but no improvement in surgical performance (Wetzel et al. 2011). This renders any direct attribution of positive effects to MP problematic. The problem is compounded in studies that reported no significant effects of MP on performance (Donnon et al. 2005; Jungmann et al. 2011; Sanders et al. 2004, 2008): lack of power calculations and manipulation checks to ensure that subjects who received MP actually had better post-intervention imagery of the surgical procedure/task at hand renders firm conclusions from these studies equally problematic.

Table 18.2 The validated Mental Imagery Questionnaire (MIQ) for the assessment of quality of mental imagery in surgical settings (Arora et al. 2010)

	1 = not at all	2	3	4	5	6	7 = very much
1. How ready or "energised" do you feel to carry out a laparoscopic cholecystectomy?	1	2	3	4	5	6	7
2. How confident do you feel to carry out a laparoscopic cholecystectomy?	1	2	3	4	5	6	7
3. How well do you think you can perform a laparoscopic cholecystectomy compared to others at your stage?	1	2	3	4	5	6	7
4. How helpful is the activity you have just been performing in preparing you to perform a laparoscopic cholecystectomy?	1	2	3	4	5	6	7
5. How easily can you "see" yourself performing a laparoscopic cholecystectomy?	1	2	3	4	5	6	7
6. How vivid and clear are the images of a laparoscopic cholecystectomy in your mind?	1	2	3	4	5	6	7
7. How easily can you "feel" yourself performing a laparoscopic cholecystectomy?	1	2	3	4	5	6	7
8. How easily would you be able to talk someone through the steps of a laparoscopic cholecystectomy?	1	2	3	4	5	6	7

Note: Laparoscopic cholecystectomy is used as an illustration. The name of the procedure of interest, depending on the focus of the assessment or training, should be used in the form.

Finally, the timing of the MP training delivery was mostly unclear or inappropriate. With the exception of the two studies by Arora et al. (2011a, b), only Immenroth et al. (2007) appears to have delivered the MP training immediately prior to the surgical procedure, and Komesu et al. (2009) delivered the MP training within 24–48 h prior to the surgical procedure—even this, however, exceeds the recommended maximum 24-h lag between training and surgery (Sapien and Rogers 2010)—although Komesu et al. did obtain some positive findings. Across the remaining studies, the timing of the MP intervention was either unclear from the reporting (Jungmann et al. 2011; Wetzel et al. 2011) or it spanned 7–14 days prior to the execution of the surgical task or procedure (Bathalon et al. 2005; Donnon et al. 2005; Sanders et al. 2004, 2008)—thereby very likely rendering the MP intervention of these studies significantly weaker. Indeed, in all of the studies that found no positive impact of MP on technical performance the timing of the mental practice was either unclear or exceeded 48 h prior to the procedure/task (Donnon et al. 2005; Jungmann et al. 2011; Sanders et al. 2004, 2008; Wetzel et al. 2011).

18.4.2.2 Measurement of Surgical Performance

All ten experimental randomised trials attempted to assess surgical performance in relation to MP, aiming to determine whether MP has a beneficial effect. Of these articles, most focused on the technical performance of the participants—in other

words, elements of performance that relate to the psychomotor execution of the surgical task or procedure of interest. Global performance assessment tools that are scored by expert surgeons (via observation) and have been previously validated within the surgical literature were used in the form of the "Objective Structured Assessment of Technical Skill" (Arora et al. 2011a; Immenroth et al. 2007; Wetzel et al. 2011), the "Global Scale of Operative Performance" (Komesu et al. 2009) and one observational assessment tool with some previous validation evidence (Sanders et al. 2004, 2008). Surgical performance was also captured via simulator-derived parameters, including time taken to complete a task (expert surgeons are typically faster) or instrument path length—the latter measure represents the distance travelled by the tip of the endoscopic instrument as captured by the virtual reality simulator (expert surgeons are typically more economical in their instrument movement; Donnon et al. 2005; Jungmann et al. 2011). Ad hoc developed performance metrics with no validation evidence were less common (Bathalon et al. 2005). Overall, this is a positive finding, as it suggests that the assessment of technical performance is more valid and reliable.

Outside technical performance, surgeons' stress was an element of their "non-technical" performance (Flin et al. 2008; Yule et al. 2006) that was captured in some studies. The recently developed "Imperial Stress Assessment Tool" (ISAT) was used in two studies (Arora et al. 2011b; Wetzel et al. 2011). ISAT comprises subjective (standardised questionnaire in the form of the "State Trait Anxiety Inventory") and objective (salivary cortisol and heart rate) parameters of human stress response. The findings of these two studies, however, were mixed: whereas Arora et al. (2011b) found reduced stress levels in the MP group, Wetzel et al. (2011) failed to show any such improvement, but found instead that MP-trained surgeons were using more strategies to cope with stress. The fact that Wetzel et al. embedded the MP intervention within a broader stress training programme, did not utilise a MP manipulation check and did not report the timing of the MP intervention may contribute to their weaker findings. In the single study that reported self-report assessment of stress (without objective parameters) no effects of MP were obtained (Sanders et al. 2008).

Finally, only one study examined surgeons' team performance using a well-validated instrument (the "Observational Teamwork Assessment for Surgery" tool)—but the study revealed null results (Wetzel et al. 2011). The methodological shortcomings of this study (mentioned above) could have contributed to the lack of effect.

18.4.3   Findings: Efficacy of Mental Practice in Improving Surgical Performance

Of the 13 studies, three assessed the hypothesised positive impact of MP on surgeons' mental imagery of a surgical procedure (Arora et al. 2010, 2011a, b). All three studies found that the mental imagery of both junior and senior surgeons formally assessed using the aforementioned MIQ tool improved significantly following MP training. A further two studies only assessed qualitatively surgeons' own perceptions

of the importance of being mentally prepared prior to a procedure. Both of these studies found that surgeons considered mental preparedness to be at least as important as their technical readiness (McDonald and Orlick 1994; McDonald et al. 1995).

Regarding surgeons' technical (psychomotor) performance, five studies found no effect of MP on a range of technical performance metrics that were used (Donnon et al. 2005; Jungmann et al. 2011; Sanders et al. 2004, 2008; Wetzel et al. 2011). In five other studies, subjects who underwent MP received higher scores on aspects of their global operative performance (Arora et al. 2011a; Bathalon et al. 2005; Immenroth et al. 2007; Komesu et al. 2009; Sanders et al. 2008).

Regarding non-technical performance, MP was shown to reduce stress (Arora et al. 2011b) and also to increase the number of stress coping strategies utilised by surgeons when faced with a surgical crisis (Wetzel et al. 2011). No impact was found of MP practice in the single, limited study that assessed surgeons' team performance (Wetzel et al. 2011).

18.5 Surgical Applications of Mental Imagery and Mental Practice: Where Next?

18.5.1 Summary of the Surgical Evidence Base

From the evidence reviewed in this chapter, a number of conclusions seem warranted concerning MP applications within surgery. First of all, although the available empirical evidence base is small, it has grown rapidly in recent years—which suggests an increasing interest in MP by surgeons. Second, although there are numerous experimental studies in the literature that employ control groups (in itself a positive aspect of the evidence base), the majority of studies that purport to evaluate MP interventions in surgery are hampered by significant methodological weaknesses. These weaknesses typically concern the use of questionable or no measures of mental imagery, reliance on inadequately validated MP interventions and deficient experimental designs. For example, no mental imagery measures or manipulation checks were implemented in the majority of studies that we retrieved and reviewed—which means that obtained effects post-training cannot be directly attributed validly to mental imagery mechanisms. Another serious methodological problem is that the time lag between intervention delivery and surgical task/procedure execution typically far exceeds the recommended 24-h window—with the likely weakening impact on MP training programmes. A third conclusion from this review is that where MP has been delivered in a reasonably robust manner, it has enhanced the technical (psychomotor) performance of (typically junior) surgeons. Finally, qualitative studies reveal that senior surgeons as well as their junior peers consider MP an important determinant of surgical excellence, report engaging in it spontaneously and call for wider implementation of MP within surgical training.

18.5.2   Key Limitations of the Evidence Base and How to Address Them

A number of limitations have become evident via the synthesis of the evidence base carried out above. Of those, we consider the following three critical but addressable in the immediate future and using currently available knowledge from the sports and psychological literatures on mental imagery and practice.

18.5.2.1   Measuring Mental Imagery

Without a direct assessment of mental imagery, it is virtually impossible to establish conclusively the internal validity of a MP surgical study. If performance improvements fail to appear it is not clear whether this is due to lack of improvement of mental imagery—and thus a weak intervention. Even if performance improvements do appear, however, it is not easy to address Hawthorne effect explanations—in others words, that improved performance is due to the intensely personalised attention and/or in-depth reflection that each participating surgeon received and/or carried out as part of the MP intervention. Assessing mental imagery in the domain of surgery is certainly no easy task as there is no single, universally agreed "gold standard" imagery measure or index available at present. Nevertheless, Collet et al. (2011) recently proposed a formula by which a novel "motor imagery index" (MII) can be calculated using a combination of six specific component scores. These scores include self-estimations of imagery quality, psychometric assessment of imagery vividness, three psychophysiological indices (derived from electrodermal and cardiac recordings) and estimation of the difference between actual and imagined duration of movement execution. Within this context, the MIQ, developed and tested by Arora et al. (2010, 2011a, b), appears to be a viable option—although it will have to be tested outside this research group to further ensure validity.

18.5.2.2   Implementation of Mental Practice Training

Despite current recommendations (Sapien and Rogers 2010), the implementation of mental imagery interventions in surgical studies has been rather poor. A very basic problem, which is relatively easy to address, is the timing of the imagery in relation to the performance of the surgical task. From this review, it appears that the shorter this time lag, the stronger and the more effective the impact of the MP intervention. Ideal time lags reported in the literature are just prior to the execution of surgery, at most 24–48 h in advance. Based on our experience, we strongly recommend shorter time lags, particularly if the surgical task goes beyond simple basic surgical tasks (like suturing and knot tying) and involves carrying out an entire operation in crisis conditions.

18.5.2.3 Assessment of Surgical Performance

Standardised performance assessment instrument, for which some reliability and validity evidence is available, is a widely recommended approach within the surgical education and safety literatures (Hull et al. 2012)—and it applies directly to MP applications within surgery. Importantly, performance assessments ought to go beyond purely technical skills to encompass non-technical aspects of performance, which include surgical leadership, communication and stress management (Flin et al. 2008; Hull et al. 2012; Vincent et al. 2004; Yule et al. 2006). Use of validated tools to capture these non-technical aspects of a surgeon's performance (e.g. the "Observational Teamwork Assessment for Surgery" tool to assess team performance or the "Imperial Stress Assessment Tool" to capture stress levels in the OR), and providing some initial training to assessors, is a necessary requirement to ensure valid and reliable measures, minimise random error and thereby increase the likelihood of obtaining true MP effects.

18.6 Future Directions: Applications of Mental Practice Within Surgical Contexts

Compared to other performance-enhancing interventions currently available to surgeons (including those that have been translated from other high-risk industries, like use of checklists and team training interventions) MP has the unique benefit of being free to all surgeons regardless of their location, stage of their careers or financial constraints of their home institutions. Mental practice can be used at all times, without requiring access to expensive training facilities. Individual surgeons can use it at their leisure, without the need of an entire operating room team to be participating. Importantly, this review suggests that MP is overall an effective means of preparing oneself prior to a procedure. It is also intuitive: senior surgeons do report exercising their mental imagery prior to entering the OR or even the night before—without necessarily realising that what they are doing has a significant evidence base to support it, in sports science, in neurological rehabilitation research and now also in surgery.

In light of the currently available evidence, we propose three recommendations to enhance the quality of future research on mental imagery and practice in surgical settings. First, it would be helpful if researchers in this field collaborated in compiling a repository of validated MP protocols for various surgical procedures. Second, these validated protocols should be used prior to surgery not only to ensure optimal, evidence-based practice of imagery interventions but also to facilitate comparison of subsequent results across relevant studies. Finally, in an effort to identify the possible theoretical mechanisms underlying imagery effects in enhancing surgical performance, it would be interesting to investigate the relationship between imagery training strategies and individual preferences for imagery types (e.g. visual object vs. spatial imagery; see Chap. 16). To conclude, despite its many limitations, research on mental imagery and MP in surgery provides a fertile domain in which

to explore important theoretical and practical issues concerning the attempt to improve skilled performance using psychological techniques. If progress continues apace in this burgeoning field, it should soon be possible to design and implement evidence-based imagery interventions that are known to be effective in enhancing designated surgical skills in real-life operating environments.

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Chapter 19
Mental Imagery and Psychopathology: Examples of Post-traumatic Stress Disorder and Bipolar Disorder

Roger M.K. Ng, Julie Krans, and Emily A. Holmes

Abstract This chapter aims to provide an update on the relation between mental imagery and psychopathology, with particular reference to post-traumatic stress disorder and bipolar affective disorder. Current evidence is provided to give an overview of the strengths and limitations of existing cognitive behavioural therapies for these two psychological disorders. Clinical vignettes are used to illustrate how imagery interventions may be incorporated into cognitive behavioural therapy to enrich the array of treatment strategies and possibly enhance its efficacy.

19.1   Imagery and Psychopathology: Is There a Special Relationship?

Mental imagery allows human beings to relive past events through retrieval from their autobiographical memories and to mentally "time-travel" into the future by imagining never-experienced events (Schacter et al. 2007). We are also more likely

R.M.K. Ng (✉)
Department of Psychiatry, Kowloon Hospital, Hong Kong, China
e-mail: ngmk@ha.org.hk

J. Krans
School of Psychology, University of New South Wales, Kensington Campus, NSW, Australia
e-mail: j.krans@unsw.edu.au

E.A. Holmes
MRC Cognition and Brain Sciences Unit, Cambridge
e-mail: emily.holmes@mrc-cbu.cam.ac.uk

to act on those events that we have simulated in imagination than those we have thought about verbally (Gregory et al. 1982). However, until recently relatively little was known about the relationship between mental imagery and emotion or its links with psychopathology.

Psychological disorders are characterised by the presence of maladaptive emotions like excessive anxiety, depressed mood, or even excessive positive emotion (see Sect. 19.3 and Chap. 20 for further discussion on the role of imagery in triggering and maintaining positive mood and desire). Because of its powerful impact on emotion and behaviour (Holmes and Mathews 2010), it is perhaps not surprising that mental imagery has been found to be associated with a number of psychological disorders. Strikingly, recurrent intrusive imagery of traumatic memories (or "flashbacks") is the hallmark of post-traumatic stress disorder (PTSD; Ehlers and Clark 2000). As traumatic experience plays a cardinal role in the aetiology of PTSD, closer scrutiny on the role of imagery in PTSD may provide some hints about the role of imagery in contributing to the onset and maintenance of other psychological disorders where trauma has been reported to play an important role.

Other anxiety disorders have also been found to be associated with intrusive negative memories of traumatic events occurring during adult life or even childhood (e.g. traumatic memories of being blamed for some adverse incident during childhood in obsessive-compulsive disorder; Speckens et al. 2007b). Patients with depression have also been found to have an excess of negative intrusive image-based memories (Patel et al. 2007). Furthermore, depressed mood is associated with a deficit in *positive* prospective imagery (Holmes et al. 2008c). Evidence has also been found that depression is characterised by a deficit in deliberately generated mental imagery during tasks of active recall, possibly due to attempts of mental suppression or avoidance of negative intrusive memories (Williams et al. 2007). Worrying, a verbal-based ruminative process found in anxiety disorders, is postulated to be a core mechanism in suppressing mental imagery and maintaining such disorders (Hirsch et al. 2012).

Recent studies have also suggested an association between mental imagery and severe mental illness. For example, people suffering from schizophrenia have been found to have a deficit in deliberately generated mental imagery of personal past memories and future events, a deficit that is associated with the severity of "positive" symptoms (D'Argembeau et al. 2008), Spauwen et al. (2006). Interestingly, there is a recent hypothesis that positive symptoms, especially auditory hallucinations (experience of hearing non-existent voices in the absence of external stimuli), might be conceptualised as a meta-cognitive misattribution of intrusive auditory flashbacks to an alien or external source (Morrison 2004). In the past few years, there have been an increasing number of studies looking into the possible role of mental imagery in the maintenance of bipolar disorder (see Sect. 19.3). In this chapter we focus on PTSD and bipolar disorder. Historically, in PTSD, trauma flashbacks have long been regarded as a mental imagery issue, whereas in bipolar disorder mental imagery has only recently been identified as a key disturbance.

19.2   The Role of Imagery in Post-traumatic Stress Disorder

19.2.1   Intrusive Memories in PTSD

During our lives, we are exposed to a wide range of events. These can be positive or negative, anticipated or unexpected. A traumatic event is extremely negative and does not fall within the range of normal expected life events. Examples of potentially traumatic events are natural disasters, interpersonal violence, and traffic- or work-related accidents. In some cases, a traumatic event can have such an impact that the survivor develops long-term psychological problems classified as PTSD (American Psychiatric Association 2000).

A hallmark feature of PTSD is the reliving of the event through mental imagery. This can be in the form of intrusively recurring memories or nightmares, for example, seeing headlights coming towards you after a car accident (Ehlers and Clark 2000). These intrusive memories are highly emotional and can be experienced with a great sense of reality, making them all the more debilitating. As to the nature of these intrusive images, a study by Speckens et al. (2007a) showed that all participants in their PTSD sample reported a visual component; sounds were part of the memory for 71% of the participants, followed by smells for 17%, and taste for 12% of the participants.

Not everyone who experiences a traumatic event develops PTSD. Having intrusive memories is a normal reaction to trauma, and a complex array of factors is involved in the actual development of PTSD. For example, individual differences, characteristics of the trauma and its aftermath, and social factors have all been shown to contribute to PTSD development (Brewin et al. 2000). Intrusive images related to trauma are not always accurate recollections but can be distorted memories or even fantasies (Ehlers et al. 2002; Hackmann and Holmes 2004; Hackmann 2011). Interestingly, it has been noted in several survey studies that therapists working with PTSD patients can develop visual intrusive images of their patient's trauma narrative (McCann and Pearlman 1990; Arvay 2001). In two controlled studies, student participants who were asked to listen to an actor-narrated "journalist report" of a traumatic traffic accident went on developing intrusive images of that event (Krans et al. 2010a, 2011). In response to hearing an account of the trauma they developed intrusive images that were strikingly similar to those reported by participants who actually watched a traffic accident film. Furthermore, the tendency to use visual imagery in daily life was positively correlated with intrusion frequency for the participants who listened to the "journalist's" account of the trauma (Krans et al. 2011). Clearly, this may have implications for therapists who listen to patients' trauma narratives.

19.2.2   Theoretical Explanations of Intrusive Memories in PTSD

One area of PTSD research focuses specifically on the question of how memories become intrusive (i.e. spontaneous and unwanted). Clinical models of PTSD suggest

that the specific encoding of the trauma predicts whether a memory will become intrusive or not (Brewin et al. 1996, 2010; Ehlers and Clark 2000; see also Holmes and Bourne 2008). High levels of stress result in a shift towards a more perceptually oriented processing mode with less verbal or conceptual processing. That is, the sensory details of the trauma (such as the sights, smells, sounds, bodily sensations) are readily encoded whereas the processing of the event on a more abstract and meaningful level is compromised. The result is a memory representation that is rich in sensory information but that lacks a clear understanding of cause and effect.

Several experimental studies have tested this "encoding hypothesis". As there are obvious limitations to experimentally investigating the encoding of trauma in memory, researchers have turned to analogue paradigms dating back to the 1960s (Lazarus and Alfert 1964; Horowitz 1969). In several studies using this paradigm, participants were presented with a film of a traumatic event (such as traffic accidents) and were given concurrent tasks to perform while watching the film (see Holmes and Bourne 2008; Krans et al. 2010b, for reviews). Afterwards, they reported their intrusive memories of the film in a diary, usually for 1 week. The encoding hypothesis proposes that intrusive images rely on an image-based memory system. Thus, reducing the amount of visual and spatial information that is encoded into this system should reduce intrusion frequency. In contrast, if processed on a verbal conceptual level, the trauma information should become more integrated into autobiographical memory thus reducing intrusion frequency. If this verbal processing is interfered with, intrusions should therefore increase. Some studies reported results in line with these hypotheses (Holmes et al. 2004, 2010; Bourne et al. 2010). However, others have reported that concurrent tasks from both modalities can reduce intrusion frequency (Krans et al. 2009, 2010a, b; Pearson and Sawyer 2011; Pearson et al. 2011). Overall, findings indicate that more sensory information will lead to more intrusive memories, but the role of verbal conceptual processing is still unclear. Mental imagery techniques, as discussed below, predominantly address these intrusive memories which themselves have a major visual component that is directly affected by mental imagery efforts.

Models from the autobiographical memory literature have also projected a view on intrusive memories in PTSD. Rather than focusing on the encoding process, this view predicts that the retrieval process determines whether a memory will be experienced as intrusive or not (Berntsen 2010; Mace 2007; Conway and Pleydell-Pearce 2000). That is, memory representations that are activated through cued-retrieval are experienced as intrusive, whereas memories that are activated as a result of a deliberate conscious search are voluntary memories. This account has received empirical support within clinical populations (e.g. Rubin et al. 2008) and analogue paradigm experiments with student participants. For example, the findings reported above that modality-specific encoding interference did not consistently account for intrusion development can be taken as circumstantial evidence to support a retrieval account of intrusive memories (Krans et al. 2009; Pearson et al. 2011). More direct experimental evidence comes from a study that showed that providing contextual information along with negative pictures increased the number of intrusive images from these pictures, rather than decreasing intrusion frequency as would be expected

from the encoding hypothesis (Pearson et al. 2011). Further, several dual task interference studies have found that voluntary memory was affected similarly to intrusive memories from a "trauma" film and that voluntary memory was positively correlated to intrusion frequency (e.g., Krans et al., 2009; 2010b). In sum, the issue of whether intrusive memories develop from specific encoding processes or from the way the memory is retrieved is an ongoing debate.

19.3   The Role of Imagery in Bipolar Disorder

The studies in the previous section have provided some evidence on the role of mental imagery (flashback memories) in PTSD, a psychological disorder with distressing negative emotions from a past traumatic event. As we shall discuss in the following section, intrusive imagery can be not only of past events but also of future events. Furthermore, imagery in psychopathology can be of any emotional state—not only negative emotions such as anxiety, shame, or guilt but also "positive" emotions such as excitement or elation. The psychological disorder typically associated with dysfunctional "positive" emotion is bipolar disorder (during mania).

Intriguingly, compared to verbal thought, mental imagery has a more powerful impact not only on our negative emotions but also on positive emotions. Holmes et al. (2008a) have found that, compared to verbally thinking about positive scenarios, imagining the same scenarios from a first-person perspective led to greater increases in positive affect (though imagining them from a third-person perspective did not). Holmes et al. (2009) extended this finding by showing that participants who generated imagery in response to a series of positively resolved ambiguous events were less emotionally vulnerable to a negative mood induction procedure than those who were asked to verbally think about the same scenarios. Further, a similar positive imagery generation task was successful in improving positive mood and enhancing behavioural performance in individuals with mild levels of depressed mood (Pictet et al. 2011).

Preliminary support for the potential clinical benefit of such imagery training procedures in reducing depressive symptoms has been provided by two small-scale clinical studies (Blackwell and Holmes 2010; Lang et al. 2012). The procedure employed in these studies uses mental imagery in combination with a "cognitive bias modification for interpretation paradigm" (CBM-I). In a positive version of CBM-I, participants are repeatedly presented with scenarios that are initially ambiguous (for example: "you keep looking at your watch and are anxiously waiting for your partner to celebrate your birthday at home") but end up being resolved in a positive way ("You hear the door bell ringing and open the door to discover that your partner is holding a bunch of red roses for you"). The role of positive mental imagery in producing mood improvement is also in line with research indicating the central role of mental imagery in fuelling "desire" and craving, such as anticipating pleasurable aspects of eating or of using recreational drugs (May et al. 2004, 2008; see Chap. 20).

Mania can be considered a pathological form of positive emotion. During manic episodes, patients tend to be over-optimistic and over-energetic and pursue unrealistic goals (e.g. buying a Ferrari in the absence of financial means, or reckless sexual encounters) with disastrous financial and social consequences. Almost all patients with mania suffer from alternating episodes of depression and mania of varying severity in their lifetime (Winokur et al. 1969; Bromet et al. 2005); this pattern is classified as bipolar disorder (American Psychiatric Association 2000). During a depressive episode, patients typically become pessimistic, socially withdrawn, and even suicidal. Bipolar disorder is therefore a severe mental illness with high morbidity and mortality (Merikangas et al. 2007). In between full-blown episodes of depression or mania, inter-episodic mood instability is prevalent and also a cause of distress (Bonsall et al. 2012).

Via the imagination of future goals, people with mania may "pre-experience" a (perhaps overly) positive future (Holmes et al. 2008b). If positive imagery can amplify positive emotion (Holmes et al. 2008a) and imagery can be regarded as a mental representation of a future goal (Conway et al. 2004), positive mental imagery might strengthen the interpretation that there is a "real" positive goal state to be achieved and acted upon in mania (Johnson 2005). Immersion in such positive imagery might further enhance confidence and lead to increased goal-directed behaviour, a common early symptom of mania (Lam and Wong 2005). Indeed, a recent study has found that students with higher levels of hypomania (a milder version of mania which might not come to clinical attention) were more likely to experience intrusive prospective mental imagery of future events (Deeprose et al. 2011). Holmes et al. (2008b) have proposed an integrated model of how positive mental imagery might amplify positive emotion, leading to the onset or recurrence of full-blown mania similar to the role played by negative imagery on amplifying anxiety symptoms.

Thus, if positive mental imagery can amplify positive emotion, it is reasonable to speculate that bipolar patients would have increased positive mental imagery during manic episodes. Recent studies have found that bipolar patients have increased intrusive imagery compared with depressed patients and healthy controls (Gregory et al. 2010; Hales et al. 2011; Holmes et al. 2011). These studies provide preliminary evidence supporting intrusive imagery as an emotional amplifier for bipolar disorder(Holmes et al. 2008a, b, c), for both positive and negative mood states. However, these studies are mainly cross-sectional in nature and cannot tease out the causal relation between positive imagery and manic symptoms, so longitudinal studies are needed.

A related hypothesis is that if intrusive imagery could act as an emotional amplifier for both positive and negative emotions, it might also contribute to the rapid mood swings associated with bipolar disorder (Bonsall et al. 2012). Those bipolar individuals with higher trait levels of imagery may be more likely to suffer from chronic inter-episode mood instability as mentioned earlier, or even from rapid cycling subtype of bipolar disorder (characterised by four or more mood episodes per year). This hypothesis was partially supported by a recent cross-sectional study showing that bipolar patients with unstable mood had

higher levels of intrusive prospective negative imagery than those with stable mood (Deeprose and Holmes, 2010). The level of such intrusive prospective imagery was also correlated with their current levels of depression and anxiety, again highlighting the potential role of negative imagery in amplifying negative emotions in mood swings.

Finally, mental imagery, with its intrinsic nature of allowing visualisation of complex structures and combination of novel ideas or fantasies with past memories, is an ideal route to creativity. There is some evidence that enhanced creativity is associated with bipolar traits (see Murray and Johnson 2010, for a review). Whether mental imagery might be a mediating factor between bipolar traits and enhanced creativity is a testable hypothesis.

19.4   Imagery Interventions and Cognitive Behavioural Therapy

Cognitive behavioural therapy (CBT) is a time-limited and structured psychological intervention which aims to identify and modify maladaptive cognitions, which are a key factor in the development and maintenance of a range of psychological disorders (Beck 1976). In the context of CBT assessment and treatments, cognitions can involve not only verbal thoughts but also mental imagery (Hackmann et al. 2011; Holmes and Mathews 2010). Imagery techniques are numerous and include evoking and reflecting on imagery; manipulating imagery to change beliefs about its significance, or learning to discriminate between imagery and reality; transforming images, memories, and dreams; and creating new mental imagery (for example promoting positive future imagery in depressed patients who have a deficit in positive imagery). Several of these techniques will be illustrated in the case studies of a PTSD and a bipolar disorder treatment below.

Hackmann et al. (2011) have recently proposed a heuristic model that places imagery interventions as a key focus of cognitive therapy (Fig. 19.1). This involves (1) educating the patient on the relation between imagery and maintenance of his or her psychological problem, as well as the value of imagery work in breaking the maintaining cycle; (2) evoking imagery in great detail; (3) observing and reflecting on imagery content and its associated meaning to come up with a diagram that illustrates the relation between imagery content and meaning and maintenance of his or her psychological problem (an imagery "micro-formulation", as the formulation centres around the relation of imagery and symptoms, in contrast to a general case formulation that depicts the relation between long-standing beliefs, maladaptive assumptions about oneself and the world, and the maintenance of psychological symptoms); and (4) troubleshooting difficulties that may emerge during imagery interventions by going through the case diagram with the patient. First we will discuss various evidence-based psychological treatments, including CBT, as applied to these two disorders.
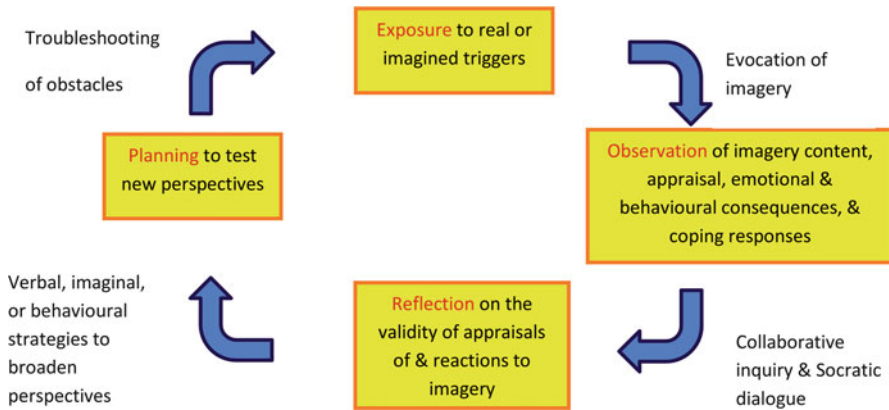
Fig. 19.1 Learning cycle for mental imagery work (adapted from Hackmann et al. 2011 Kolb, 1984)

19.5 PTSD Treatments and Imagery

19.5.1 Cognitive Behavioural Therapy: Imaginal Exposure

Prolonged exposure therapy (PE; Foa et al. 1991) is one of the most widely disseminated and recommended treatment protocols for PTSD (e.g. National Institute for Clinical Excellence 2005; Foa et al. 2009). PE relies heavily on imaginal exposure to the memory of the traumatic event, during which the patient imagines the event as vividly as possible and describes it to the therapist. The session is audiotaped, and the patient is instructed to listen to the recordings at home. With repeated reliving, the patient habituates to the distress elicited by the trauma memory. Other effective components of CBT include exposure in vivo (during which the patient is exposed to feared objects, situations, or activities related to the trauma) and cognitive techniques to correct dysfunctional beliefs (Bryant et al. 2003). A recent meta-analysis has shown that PE is more effective than waiting list or placebo control conditions (Hedge's $g = 1.51$ and 0.65, respectively; Powers et al. 2010) and as effective as other recommended active psychological therapies such as eye movement desensitisation reprocessing (EMDR; Powers et al. 2010). Furthermore, comorbidity, which is common with a PTSD diagnosis, does not appear to be a contraindication for a PE treatment of PTSD (Hagenaars et al. 2010). There are, however, some downsides to PE. The imaginal exposure can initially increase arousal (Foa et al. 1991), and high levels of dropout have been reported for therapies with 60-min exposure sessions (25–51%; Arntz et al. 2007).

Another key intervention is cognitive therapy (CT) which has a strong focus on modifying dysfunctional appraisals of the trauma and its consequences (Ehlers et al. 2005). This technique is consistent with other CBT interventions, but rather than working from a habituation model, the goal of reliving the trauma is to identify

dysfunctional appraisals and create a coherent and updated conceptual memory that discriminates "then" from "now" (Ehlers et al. 2005). Techniques to transform the trauma imagery are also incorporated. Initial meta-analysis data shows good treatment effects (Cohen's $d=2.70$) as well as lower dropout rates (3%), presumably because of fewer sessions focusing on imaginal exposure (Ehlers, et al. 2005; Speckens et al. 2006).

19.5.2 Imagery Rescripting

Imagery rescripting (IR) was initially formulated as a schematic treatment for childhood abuse (Smucker et al. 1995; Smucker and Niederee 1995; Arntz and Weertman 1999). More recently, IR has been used as an intervention to target distressing imagery (Holmes et al. 2007). In general, IR takes mental imagery a step further by actively engaging with the trauma memory and/or altering it so that the meaning of the trauma is transformed into a more healthy view (Hackmann 2011; Hackmann et al. 2011). Intrusive memories of trauma may not be a direct representation of the actual event but can involve distorted information. Activating the image provides an opportunity to update the image with correct information from the present (e.g. "I did not die"), or to change the way one responded during the event. This can induce a sense of mastery and reduce feelings of guilt.

Often an intrusive memory is of the worst moment of the trauma or "hotspot" (Grey et al. 2001; Grey and Holmes 2008). Sometimes, the person remembers this worst moment but does not move beyond that point. For example, someone may re-experience lying on the street badly injured, thinking "I'm going to die", but may not remember being brought to hospital and recovering from their injuries. Imagery rescripting can be used to extend the image to include the positive outcome (see Hackmann 2011; Hackmann et al. 2011).

Empirical studies suggest that IR has an additive effect to PE but may be less distressing for the therapist and the patient (Arntz et al. 2007). IR has also been found effective for PE non-responders (Grunert et al. 2007). A recent experimental study using a trauma analogue paradigm (Hagenaars and Arntz 2012) found that IR was more effective in reducing the frequency of intrusions than positive imagery and PE and was experienced as less distressing than PE.

19.5.3 Eye Movement Desensitisation Reprocessing

EMDR is an integrative approach (Shapiro 1989, 1991, 1999), combining elements from different traditional psychotherapies. It has been reviewed as equally successful as CBT (e.g. Bisson et al. 2007). The component that has received the most attention is "dual tasking" during recall of the trauma memory in a therapeutic session. The patient is instructed by the therapist to use mental imagery to activate the trauma memory while performing an active (e.g. eye movements) or passive task

(e.g. listening to beeps). Usually, the time of exposure to the trauma memory is shorter than in PE interventions. During and immediately after eye movements during recall, the emotionality and vividness of an aversive memory is reduced. This effect was still found at 1 week follow-up (e.g. Kavanagh et al. 2001; Kemps and Tiggeman 2007; Gunter and Bodner 2008; Engelhard et al. 2010). Other taxing dual tasks, such as counting or drawing, have been found to be effective as well (e.g. Engelhard et al. 2011; Gunter and Bodner 2008).

A debate has been ongoing about whether the dual tasks effects are modality specific (i.e. visuospatial versus verbal) or can be explained by a general processing load. A study by van den Hout et al. (2011) suggested that the majority of the effect is from a central executive load, with an additional (smaller) modality-specific effect. That is, although the largest effect comes from doing a second, demanding task, a visuospatial task will interfere a little more with visual images than a verbal task, whereas the opposite holds for auditory images (Kemps and Tiggeman 2007).

19.5.4 Case Study of a Cognitive Behavioural Therapy for PTSD

The case study in Box 19.1 illustrates an imaginal exposure component of a CBT treatment for PTSD. Because the reliving was so overwhelming the therapist used additional imagery techniques in order to reduce the dissociative response. Other examples have been described by Jaycox and Foa (1996). Shifting the perspective in imagery finds its rationale in research showing that imagery from a field perspective is more emotional and real than imagery from an observer perspective (McIsaac and Eich 2004; Holmes and Mathews 2010). Although a field perspective is recommended for reliving (Foa et al. 1991) and has been found to be associated with better psychological health (Kuyken and Moulds 2009), in this case an observer perspective was used in order to decrease the levels of initial distress elicited by the reliving in field perspective so that emotional processing could take place but was not so strong it prompted a dissociative reaction (Jaycox and Foa 1996).

19.6 An Example of Cognitive Behavioural Therapy for Bipolar Disorder

CBT for bipolar disorder is less well developed than CBT for PTSD, and better understanding aspects such as imagery may help refine our treatments for this complex disorder. Current CBT for bipolar disorder places heavy emphasis on psycho-education about the nature of the illness using a stress-diathesis model. The model emphasises the interaction of genes and environmental stress in triggering the onset and relapse of

Box 19.1 Case Study of Imaginal Exposure in PTSD

"Reza" was a 30-year-old refugee from Iran, who had fled the country a year earlier. Soldiers had come into her home and had taken away her husband. She was afraid that she would never see him again. The soldiers returned to Reza's house and took her and her 8-year-old son. During their imprisonment, Reza was repeatedly beaten and raped in front of her son. After several weeks, they were released and fled the country.

In their new country, Reza reported anxiety symptoms to her general practitioner, who referred her to an outpatient anxiety clinic. Reza presented with repetitive flashbacks and nightmares, trouble falling asleep, irritability, fear of being home alone or with her son, an exaggerated startle response especially in response to hearing footsteps, and hyper-arousal. Her symptoms were classified as PTSD and CBT was recommended.

The treatment consisted of prolonged imaginal exposure, exposure in vivo, and cognitive restructuring. In the first session, the therapist provided Reza with psycho-education on how PTSD develops and explained to her the importance of reliving the trauma in a safe way in order to habituate to the fear. In the second session, Reza worked with her therapist to make a hierarchy of events in terms of how distressing they were. As the list was dominated by memories of trauma it was decided to start with imaginal exposure.

During the following sessions, 45 min was spent imaginally reliving specific trauma memories. The therapist instructed Reza to close her eyes and imagine the event as vividly as possible looking through her own eyes (field perspective) and describe it to the therapist in the present tense. The sessions were taped, and Reza listened to the recordings everyday while imagining the event. During the imaginal exposure, Reza sometimes got so involved that she showed a dissociative response and seemed to lose touch with reality. On one occasion, she jumped up and ran out the door convinced that soldiers had come into the room to take her away. Because of these strong dissociative responses, habituation to the memories did not occur, and her distress did not fade.

The therapy continued with imaginal exposure, but the therapist instructed Reza to no longer close her eyes during reliving and to tell the story as if it were happening to someone else (observer perspective). By having her eyes open, Reza was more readily able to stay in touch with the here-and-now. After this change in technique, her distress and anxiety decreased during the reliving. After repeated session of this procedure and towards the end of the therapy, she was able to recount the trauma story imagining in the first person (rather than observer perspective) without losing touch with reality, and her distress had decreased to an acceptable level. This was associated with a reduction in her intrusive flashback memories to the trauma and improvement in her other PTSD symptoms.

illness, cognitive and behavioural techniques to cope with early signs and symptoms of recurrences, and enhancing medication adherence (Newman et al. 2002; Lam et al. 2010). Additional strategies include advocating a stable lifestyle to minimise major disruption of the sleep-wake rhythm, monitoring and rating mood in response to events in daily life to discriminate between normal and pathological mood swings, and the use of different strategies during different mood states (Newman et al. 2002; Lam et al. 2010).

Lam et al. (2003) found that patients with remitted bipolar disorder receiving a course of cognitive therapy had a lower risk of manic and depressive recurrences and longer time to first recurrence, compared with patients receiving treatment as usual (medication plus regular psychiatric follow-up). A 2-year post-therapy follow-up study of the sample found maintenance of initial gain, with stronger effects for depression than for mania (Lam et al. 2005). A replication study with a larger sample size had less encouraging results, with no overall benefits (Scott et al. 2006) but has been criticised as having a heterogeneous study sample (32% of participants being in acute mood episode) and an inadequate number of sessions to deal with therapy work on managing acute mood episode and on relapse prevention (Lam 2006). Nevertheless, the study highlighted the current limitations of the efficacy of current versions of cognitive therapy for bipolar disorders even in a research setting with high level of expertise and intensive supervision (see Scott and Colom 2008). Thus, there is a need to develop more effective treatments.

Treatments to date in this area have been focussed on traditional verbal cognitive processing and verbal CBT techniques. We suggest that a focus on mental imagery may contribute to the improved efficacy of CBT for bipolar disorder (Holmes et al. 2008a, b, c). Different phases of bipolar disorder might be associated with different types of intrusive imagery (Gregory et al. 2010). Theoretically, direct techniques such as transforming the content or outcome of imagery might moderate the maladaptive appraisal of the imagery during both manic and depressed phases of bipolar disorder. For example, a person in depressed phase of bipolar disorder may experience a negative intrusive memory of being left alone at home after a major quarrel with their spouse in the form of a "snapshot" image. Such negative images can be manipulated to "go beyond the worst point" to assist that person to recall that they have indeed survived the break-up and incorporate an "updated" image of them playing happily with their dog at home (see Holmes et al. 2007). Similarly, positive, over-expansive intrusive imagery of a patient driving a red Ferrari in Las Vegas could be manipulated to "go beyond the toxic point" to see the financial debt after such an extravagant purchase.

So far, there are no methodologically rigorous studies that look into the efficacy of such imagery intervention techniques for the treatment or prevention of manic or depressed phases of bipolar disorder. However, the experimental evidence of a relation between mental imagery and bipolarity suggests that this avenue may be fruitful. Future research should attempt to clarify the value of imagery interventions for bipolar patients and to determine whether it contributes to improved mood stability.

Box 19.2 Case Study of Intrusive Positive Imagery in Bipolar Disorder

Robert was an 18-year-old high school student who was admitted into an acute psychiatric ward because of a 2-week history of elated mood, increased irritability towards his parents and classmates, and grandiose ideas of being accepted into a prestigious university in the city. Upon admission, Robert was noted to be over-friendly to his psychiatrist and talked incessantly about his creative ideas and his future promising career as a famed scientist. When asked to produce evidence of his admission to the prestigious university and his conviction about his future fame, he reported that 1 month earlier he saw himself in recurrent dreams and in daytime imagery wearing a graduation gown and mortar-board to attend a graduation ceremony. As the positive imagery was so involuntary and vivid in his mind's eye, he appraised it as real and as a "prophecy for his future success" (a meta-cognitive appraisal Wells (2000)). He felt excited about the sights and sounds of attending the graduation ceremony in the hall with the applause of the guests. His positive emotion was further amplified when he ruminated about his elation and recalled his recent positive memory of receiving the best student award.

Robert was diagnosed as suffering from mania. Robert was extremely reluctant to adhere to the prescribed mood stabiliser medication, as he felt that his beliefs were well supported by past evidence, positive memories, and indeed his future imagery of this "coming true". After reframing the mood stabiliser as a helpful medication to improve his sleep and to normalise his sleep–wake cycle disrupted during his period of excitement, Robert eventually agreed to take medication as a "behavioural experiment" to see if his sleep would improve after 1 week. His manic symptoms became less intense after supervised treatment in the inpatient ward. He was less excited and talkative and became less boastful. However, he still reported having some intrusive positive imagery.

The therapist tried to normalise his positive imagery as being similar to positive goals that young people strive to achieve so as to reduce his feelings of resistance about open discussion of his imagery. Robert was then facilitated to describe the content of the positive imagery in detail (including its visual, auditory, tactile, and olfactory components) and to reflect on its meaning. It became apparent that he was a diligent high school student who strived towards academic success. He also attributed his creativity in arts to his strong tendency to visualise his complex ideas. He therefore regarded all his daytime fantasies, dreams, and intrusive imagery as important hints about his future goals and success.

A case formulation centred on mental imagery was developed collaboratively between Robert and his therapist (Fig. 19.2). The rationale of imagery intervention strategies was then explained using this case formulation, thereby enhancing his acceptance of and adherence to the imagery interventions.
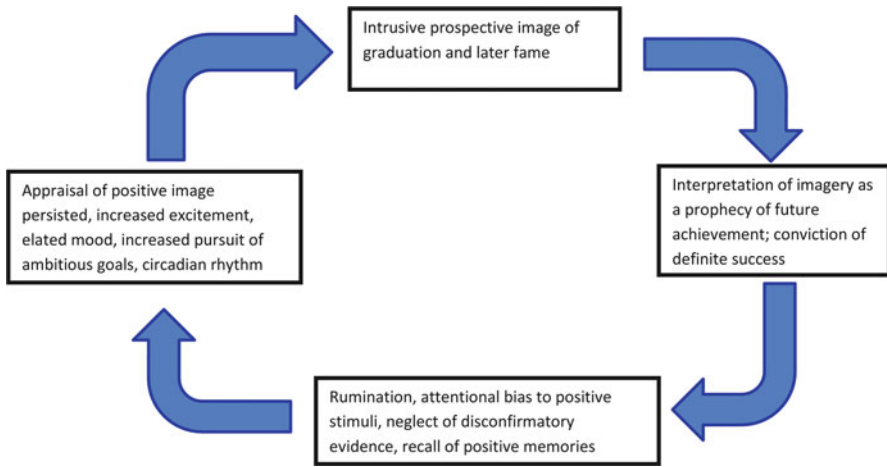
Fig. 19.2 Micro-formulation of positive imagery for Robert with bipolar disorder

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Box 19.2 (continued)

Robert was invited to list the similarities and differences between "future goals to be attained" and "prophecy". He was also invited to conduct a behavioural survey of his family members and friends about their views of positive imagery and prophecy. Robert discovered via the survey that positive imagery could be a motivator for goal attainment but that it was not a guarantee of success in attaining the goal. In fact, his friends suggested that ruminating excessively on the content of imagery and attributing prophetic power to it would divert his energy and talent away from working towards his desired goal. His meta-cognitive appraisal of the predictive power of positive imagery and his tendency to ruminate on it were thereby weakened.

Further imagery interventions were conducted to manipulate the content of his imagery, for example, asking Robert to put the positive imagery on a television screen and then to switch off the television and also to think beyond the "toxic point of fame and glory of a successful scientist" to the work burden of endless lonely nights conducting research and writing academic papers in order to maintain such scientific fame. Finally, Robert was supported to accept the grief of losing his particularly cherished positive imagery and the positive feelings associated with mania, as his manic symptoms gradually subsided with pharmacological treatment and cognitive therapy.

His manic phase was followed by a brief period of mild depression (his diagnosis was thereby also revised to bipolar affective disorder). The therapist helped Robert to accept the loss, reframe his failure as learning opportunities to prepare for future success, as well as to create a more realistic positive imag-

(continued)

Box 19.2 (continued)

ery that focused on short-term goals (in his case, a positive image of him sitting calmly, smiling contentedly, and focusing his attention on his study material in his bedroom). Further booster sessions were provided after his hospital discharge to encourage a regular sleep–wake rhythm; to differentiate between normal and pathological mood swings using a mood chart, activity schedule; and to keep an imagery diary, since the onset of intrusive positive imagery of attainment of difficult and remote goals appeared to be an early symptom of his mania. He was also told to practise manipulating both positive and negative imagery to challenge his belief about the prophetic value of imagery.

19.6.1 Case Study of Imagery-Informed Cognitive Behavioural Therapy for Bipolar Disorder

The clinical vignette in Box 19.2 illustrates how a patient with bipolar disorder might experience intrusive positive imagery of future success during the onset of mania. The meta-cognitive appraisal of such positive intrusions can lead to increased self-confidence, positive rumination, and risky behaviour. A case formulation highlighting this imagery (an "imagery micro-formulation") was used to help the patient to make sense of the symptoms, as well as to provide a clear rationale for a subsequent imagery intervention.

19.7 Conclusions

In this chapter we have illustrated ways in which mental imagery can play a prominent part in psychopathology, using the examples of PTSD and bipolar disorder. We have also illustrated that a mental imagery focus can be used in well-established treatment techniques (e.g. imaginal exposure for PTSD) and also in considering how to improve treatments such as CBT (e.g. for bipolar disorder). It is striking that mental imagery is still underexplored in mental health and treatment research (Holmes and Mathews 2010). A better understanding of mental imagery in relation to basic emotions, and also across psychological disorders, is required. More basic research is also needed in this regard including perspectives from experimental psychopathology, cognitive science, and neuroscience. As well as working with patient groups it would be extremely helpful to address fundamental questions using general population samples that might vary in traits such as anxiety, depressed mood, bipolarity, and so on. Doing so may help us address fundamental questions about mental imagery (in its many and various aspects) in relation to basic emotions and also to psychopathology. This territory clearly requires more researchers with an interest in mental imagery from a variety of angles.

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Chapter 20
Imagery and Cravings

Eva Kemps and Marika Tiggemann

Abstract Craving has been a much researched topic for several decades. However, research into its imagery basis is relatively new. This chapter reviews recent literature in support of a role for mental imagery in craving. In particular, it presents converging evidence from anecdotal reports and laboratory studies that sensory images are a key feature of any craving experience. Additionally, it describes empirical work showing that imagery can be used to induce cravings. Importantly, the chapter also reviews empirical data which show that imagery can conversely be used to reduce cravings. The latter is all the more important in view of the potentially negative consequences that can arise from cravings.

Keywords Imagery • Craving • Craving induction • Craving reduction

20.1 Introduction

Craving is a topic of current scientific and public interest. Themes of drug and alcohol craving are commonly portrayed in books, films and other popular media. The word *craving* itself is also very much part of our everyday vocabulary and applied to many things from drugs to gambling. Advertising campaigns in particular use it in their slogans, for example, to promote the sale of chocolate.

Within the scientific literature, craving has been a much researched topic for several decades. However, research into its imagery basis is relatively new. This chapter reviews recent literature in support of a role for mental imagery in

E. Kemps (✉) • M. Tiggemann
School of Psychology, Flinders University,
GPO Box 2100, Adelaide, SA 5001, Australia
e-mail: Eva.Kemps@flinders.edu.au

craving. In particular, it presents converging evidence from anecdotal reports and laboratory studies that sensory images are a key feature of any craving experience. Additionally, it describes empirical work showing that imagery can be used to induce cravings. Importantly, the chapter also reviews empirical data which show that imagery can conversely be used to reduce cravings. The latter is all the more important in view of the potentially negative consequences that can arise from cravings.

20.2 Craving

20.2.1 Definition

The term "craving" refers to a motivational state whereby an individual feels compelled to seek and ingest a particular substance (Baker et al. 1986). It usually refers to alcohol, tobacco or drugs but can also be applied to food, coffee, coke and other caffeinated beverages, as well as activities that do not involve ingesting substances such as gambling, and even sport. At a neurological level, all cravings rely on the same reward system, i.e. the mesolimbic dopaminergic system. This system also regulates "normal" eating, which explains why the same stimulus (e.g. a packet of biscuits) can induce both adaptive and maladaptive behaviours.

Our own interest has been in food cravings. These have been described as an intense desire or urge to eat a specific food (Weingarten and Elston 1990). It is this specificity which distinguishes food cravings from ordinary food choices and hunger (Pelchat 2002). Hunger signals a physiological need to eat, which can be satisfied with any food. Cravings, however, are for a particular food and can only be satisfied by eating that food. For example, we crave macadamia and caramel ice cream, rather than something generically sweet.

20.2.2 Origin

The origin of cravings has been attributed to a range of both physiological and psychological factors. At a physiological level, the main trigger is a state of deprivation (Jorenby et al. 1996), which is often accompanied by symptoms such as an increased heart rate (Sayette et al. 2000). In the food domain, hormonal changes during the menstrual cycle (Dye et al. 1995) and pregnancy (Dickens and Trethowan 1971) have also been associated with cravings in women. At a psychological level, cravings can be triggered by both internal and external factors. Internal triggers include negative emotional states, such as feelings of boredom, loneliness, depression, anxiety as well as stress (Hill et al. 1991; Maude-Griffin and Tiffany 1996). External triggers include

exposure to environmental cues, such as the smell of a burning cigarette (Sayette and Hufford 1994) or the sight of tasty food (Fedoroff et al. 2003).

20.2.3 Consequences

Cravings for substances such as alcohol, tobacco and drugs often give rise to negative consequences. For instance, they are a major withdrawal symptom when substance use is resisted (e.g. an alcoholic who is trying to give up drinking) or prevented (e.g. a heroin addict undergoing a drug rehabilitation programme) (Hughes and Hatsukami 1986). Cravings therefore make it hard for people to quit substance use. Even in people who have quit successfully, cravings can often trigger a relapse (Shiffman et al. 1997). Cravings can also lead to the development and maintenance of addiction (American Psychiatric Association 2000). This can in turn lead to physical and mental ill health, unemployment, crime (e.g. theft, domestic violence) and in some cases death (United Nations Office on Drugs and Crime 2010). It is estimated that the economic cost of substance abuse in the United States alone exceeds $600 billion annually (National Institute on Drug Abuse 2011).

In contrast to cravings for alcohol, tobacco and drugs, cravings for food are not necessarily pathological. In fact, food cravings are a common and everyday experience (Lafay et al. 2001), with prevalence rates varying according to gender and age. Women tend to crave more than men, with women craving more sweet and men more savoury foods (Weingarten and Elston 1991), and younger people crave more than older people (Pelchat 1997). There are also marked cross-cultural differences in the kind of foods that are craved (Hawks et al. 2003). For example, chocolate is the most commonly craved food in Western societies (Hetherington and Macdiarmid 1993), followed by chips, pizza, cake and ice cream. In Egypt, on the other hand, the most craved foods are vegetable dishes, some stuffed or cooked with meat (Parker et al. 2003).

Nevertheless, food cravings can be maladaptive for some people and even pose health risks. Specifically, food cravings can trigger possible feelings of guilt and shame if followed by unwanted consumption (Macdiarmid and Hetherington 1995). Food cravings also have the potential to disrupt and thwart dieting attempts. In support, research shows that food cravings have been linked to early dropout from prescribed weight-loss programmes (Sitton 1991). Importantly, food cravings have been identified as a precursor to binge eating (Gendall et al. 1998; McManus and Waller 1995), itself a risk factor for the development of obesity (Schlundt et al. 1993) and eating disorders, particularly bulimia nervosa (Mitchell et al. 1985; Waters et al. 2001).

Like food cravings, cravings for caffeine also occur among a large proportion of the general population without any problem. However, they have also been associated with negative consequences, particularly when translated into habitual caffeine consumption. Regular caffeine use, especially in moderate to high doses, can pose health risks, such as elevated blood pressure, insomnia, anxiety, an aggravated response to stress, an increased risk of cardiovascular disease and physical dependency (Griffiths et al. 2003; James 2004).

20.3   A Role for Mental Imagery in Craving

While initial investigations have focused primarily on documenting the phenomenology, antecedents and consequences of cravings, more recent research has turned to the underpinnings of the actual craving experience itself. Converging evidence from a number of different sources points to mental imagery as a key component of craving episodes.

First, anecdotal reports of naturally occurring craving experiences show that when people crave, they have vivid images of the craved substance. For example, smokers commonly report images of cigarette packets, relaxing and enjoying a cigarette or having a cigarette to help cope with stress when they crave a cigarette (Salkovskis and Reynolds 1994).

Second, more formal surveys of everyday cravings corroborate the key role played by mental imagery in craving. For example, May et al. (2004) reported that respondents strongly endorsed imagery-based descriptors (e.g. "I am visualising it") as characteristic of their cravings for a range of substances including tobacco, alcohol, chocolate and soft drinks. Likewise, we (Tiggemann and Kemps 2005) subsequently found that respondents spontaneously use imagery terms to describe their food cravings. Specifically, we found that 30% of our undergraduate student sample used phrases such as "I could picture the pizza in my mind, picture eating it" when we asked them to write a short paragraph describing a previous food craving episode.

Across substances, people generally experience visual, olfactory and gustatory images when they crave. In support, questionnaire studies show that respondents rate imagery-based descriptors in these three sensory modalities (e.g. "I imagine the sight/smell/taste of it") very highly; in contrast, auditory and tactile descriptors (e.g. "I imagine the sound/texture of it") are not highly rated (Kemps and Tiggemann 2009; May et al. 2004, 2008; Tiggemann and Kemps 2005). Furthermore, when we (Tiggemann and Kemps 2005) asked participants to assign specific percentages to each of the five sensory modalities involved in an imagined food craving experience, the visual modality (39.7%) scored the highest, followed by the gustatory (30.6%) and olfactory (15.8%) modalities. The tactile (9.5%) and auditory (4.4%) modalities were again little used. Together, these findings show that cravings for a wide range of substances are characterised primarily by visual, olfactory and gustatory sensory images, with limited involvement of auditory or tactile images.

Third, a recent theoretical account of cravings, the Elaborated Intrusion Theory of Desire, proposes that sensory images are at the very heart of the craving experience (Kavanagh et al. 2005). According to this theory, cravings are triggered by intrusive thoughts about a desired substance. These thoughts are pleasurable and therefore encourage the individual to enrich and elaborate them. This elaboration process involves a controlled search for relevant information about the substance in long-term memory (e.g. the smell of hot chocolate pudding and how good it tasted when your mother made it last Sunday). This information is then manipulated and retained in working memory, in the form of vivid, quasi-lifelike mental images. These desire-related images are initially rewarding but ultimately become distressing because they intensify the individual's awareness of not having the substance if its acquisition is delayed or prevented.

20.4 Imagery Induces Craving

Further evidence for a role for mental imagery in craving comes from laboratory studies that have used imagery to experimentally induce a craving in research participants. In fact, the use of imagery scripts is a common craving induction protocol, alongside substance deprivation (i.e. instructing participants to abstain from the craved substance for a set period of time before the laboratory session) and in vivo cue exposure (i.e. exposing participants to the actual substance in the laboratory without allowing them to consume it) (Carter and Tiffany 1999).

Imagery scripts present participants with some sort of scenario that is designed to make them crave. Participants are instructed to create an image of the situation described in the scenario and to bring the experience to mind as clearly and as vividly as they can, with as much detail as possible, as if it were happening right now. For example, several studies have presented cigarette smokers with various smoking scenarios (e.g. smoking at a party with friends) and asked them to imagine themselves participating in these scenarios (Maude-Griffin and Tiffany 1996; Tiffany and Drobes 1990; Tiffany and Hakenewerth 1991). Participants are then asked to rate the vividness of their image and their urge to smoke. This protocol has been shown to successfully induce cigarette cravings in the laboratory. Moreover, imagery has been shown to be an equally effective methodology for eliciting cigarette cravings as both smoking deprivation and in vivo exposure to a lit cigarette (Drobes and Tiffany 1997).

Similar observations have been reported for imaginal induced cravings for opiate in drug addicts (Hillebrand 2000), for coffee in habitual coffee drinkers (Kemps and Tiggemann 2009) and for food across the board. For example, Harvey et al. (2005) showed that food cravings increased following the simple instruction to imagine a food scenario ("Imagine you are eating your favourite food").

Other compelling support for the imagery basis of craving comes from reports of a positive correlation between participants' self-reported vividness of an imagined urge-related scenario and their level of craving. In other words, stronger cravings are associated with more vivid images. This relationship between imagery vividness and craving intensity has been reported consistently and across substances (Drobes and Tiffany 1997; Harvey et al. 2005; Maude-Griffin and Tiffany 1996; May et al. 2008; Tiffany and Drobes 1990; Tiffany and Hakenewerth 1991).

20.4.1 Consequences of Imaginal Induced Craving

Imagery scripts not only elicit the intended cravings. They can also affect mood, physiological responses and cognition. For example, Cepeda-Benito and Tiffany (1996) asked regular smokers to rate the level of positive as well as negative mood while they imagined either a smoking or a non-smoking (e.g. watching and admiring a fireworks display) scenario. Imagining a smoking scenario not only elicited

stronger cigarette cravings but also produced lower positive and higher negative mood ratings than imagining a non-smoking scenario. In addition, the researchers monitored the participants' heart rate and skin conductance levels. There was a significant group difference for both these physiological measures, with participants who imagined a smoking scenario showing faster heart rates and greater skin conductance. Similar increases in these and other physiological responses (e.g. finger temperature, sweat gland activity) have been shown following imaginal induction of cravings for alcohol (Weinstein et al. 1998) and drugs (Sinha et al. 2000).

Another consequence of cravings induced by imagery scripts is cognitive impairment. The earliest laboratory studies used a simple reaction time task to examine the cognitive effects of craving. These have shown that imaginally induced cravings slow response times. For example, in a study of the cognitive effects of cigarette craving, regular smokers created images of smoking or non-smoking scenarios (Cepeda-Benito and Tiffany 1996). Following the imaginal induction protocol, participants performed a computer-based reaction time task in which they had to press a button as quickly as possible whenever they heard a tone. Participants who imagined smoking scenarios reported stronger cigarette cravings and exhibited longer response latencies than those who imagined non-smoking scenarios.

Similar increases in response times have also been shown in opiate users and weight-loss dieters following imaginal induction of drug and food cravings, respectively (Green et al. 2000; Hillebrand 2000). In particular, adopting a similar dual-task paradigm, Green et al. (2000) reported a correlation between latency on a simple reaction time task and self-reported desire to eat in dieters and restrained eaters. Specifically, participants were slower to respond following instructions to imagine a food scenario ("Imagine you are eating your favourite food"), but not a non-food scenario ("Imagine you are on your favourite holiday").

Cognitive impairment following imaginal craving induction is not restricted to slower reaction times to stimuli on a simple reaction time task, but also occurs on other, more complex tasks. In particular, in a series of studies Zwaan and colleagues (Madden and Zwaan 2001; Zwaan et al. 2000; Zwaan and Truitt 1998) showed that cigarette cravings induced via an imagery script impaired language comprehension and mental arithmetic in smokers. Half the participants imagined a scenario about smoking (i.e. smoking after a satisfying meal in a restaurant); the other half imagined a scenario that was devoid of any smoking content (i.e. relaxing and enjoying the view from a window). For the language comprehension task, participants read sentences and answered true–false questions about them. In the mental arithmetic task, participants verified complex addition problems. Smokers who had imagined the smoking scenario reported stronger cigarette cravings and made more errors on both the sentence comprehension and mental addition tasks than those who had imagined the non-smoking scenario. More generally, we have shown that chocolate cravings similarly impair performance on complex memory tasks (Kemps et al. 2008b; Tiggemann et al. 2010).

Theoretically, the adverse cognitive effects of imaginal induced cravings can be readily explained by the Elaborated Intrusion Theory of Desire (Kavanagh et al. 2005). Specifically, the generation and maintenance of craving-related images takes up limited

working memory resources, leaving fewer resources available for competing cognitive demands, such as a reaction time task, and consequently, task performance suffers.

In everyday life the cognitive effects of any individual craving episode are likely to be small. They may nevertheless be important, particularly where split-second responses are crucial, for example, when manoeuvring through dense traffic. Unsatisfied cravings in such situations have the potential to increase accidents. Moreover, there is an abundance of substance cues in our contemporary environment (e.g. fast food outlets, bottle shops, advertisements on television or billboards) that are likely to induce cravings.

20.5   Imagery Reduces Craving

Because of the negative consequences that can arise from cravings (see Sect. 20.2.3), the development of effective craving-reduction techniques clearly has practical importance. However, contemporary intervention tools involving either suppression of craving-related thoughts or unreinforced exposure to substance cues have not proven very successful. Indeed, several studies have shown that attempting to suppress thoughts about smoking (Salkovskis and Reynolds 1994) or chocolate (Johnston et al. 1999) ironically increases such thoughts. Likewise, Hetherington (2001) found that exposing individuals to a craved food but not allowing them to eat it does very little to reduce their cravings. Thus there is a need for new and different craving-reduction techniques.

The above findings of cognitive impairment following imaginal craving induction (see Sect. 20.4.1) show that cravings and other tasks compete for the same limited cognitive resources. This raises an intriguing possibility for craving reduction. Specifically, just as (imagery induced) cravings reduce cognitive task performance, then conversely, it may be possible to use cognitive tasks to reduce cravings. Indeed the Elaborated Intrusion Theory of Desire (Kavanagh et al. 2005) predicts that tasks that place demands on the same cognitive processes as those that support craving-related imagery should prove the most effective in reducing craving. As cravings are characterised predominantly by visual, olfactory and gustatory images, with little involvement of auditory and tactile images (Kemps and Tiggemann 2009; May et al. 2004, 2008; Tiggemann and Kemps 2005) (see Sect. 20.3), the Elaborated Intrusion Theory of Desire predicts that a competing visual, olfactory or gustatory task would be maximally effective at reducing cravings.

To test this prediction, we (Kemps and Tiggemann 2007) first induced food cravings and then asked participants to rate their craving intensity. They were then randomly assigned to perform one of three imagery tasks: visual, auditory or olfactory. Participants were asked to form a series of images of common sights (e.g. "Imagine the appearance of a rainbow"), sounds (e.g. "Imagine the sound of a siren") or smells (e.g. "Imagine the smell of eucalyptus"). Following the imagery task, all participants again rated their level of craving. As predicted, the visual and olfactory imagery tasks reduced reported cravings for food in general (Experiment 1) and for chocolate in

particular (Experiments 2 and 3), but the auditory task did not. In an analogous study, Versland and Rosenberg (2007) showed that imagery scripts that asked smokers to focus on the sights and/or smells associated with being on a beach reduced cigarette cravings. More recently, visual and olfactory imagery tasks have been shown to suppress caffeine cravings in habitual coffee drinkers (Kemps and Tiggemann 2009). Thus competing visual and olfactory imagery tasks may reduce cravings.

20.5.1   Simple Craving Reduction Tasks

The formation and retention of visual or olfactory images is both time-consuming and cognitively effortful and hence is unlikely to be an effective craving reduction technique. Alternative, simpler and less demanding tasks in the visual domain include viewing dynamic visual noise. This involves watching a flickering pattern of random black and white dots, similar to snow on an untuned television screen (Quinn and McConnell 1996). Experimental analogues of post-traumatic stress disorder have shown that dynamic visual noise can successfully reduce the vividness and consequent emotional impact of distressing images (Kavanagh et al. 2001; see also Ng et al. Chap. 19). We (Kemps et al. 2004, 2005, 2008a; McClelland et al. 2006; Steel et al. 2006) adopted a similar paradigm to investigate the craving reduction capacity of this simple visual task. Based on the logic of the Elaborated Intrusion Theory of Desire, we argued that dynamic visual noise would reduce food cravings by interfering with the imagery associated with the craving.

In a series of studies, we elicited food cravings by asking participants to form images of highly desired foods (e.g. chocolate, cake, pizza) and then to hold these in mind while watching a dynamic visual noise display. In some studies the images were elicited by pictures of foods; in others they were generated from verbal cues. As predicted, dynamic visual noise reduced the vividness of participants' food images relative to a control condition or an auditory equivalent which presented irrelevant speech (i.e. listening to a recording of a newspaper article read in a foreign language; Salamé and Baddeley 1982). Importantly, there was also a concomitant reduction in participants' level of craving for these foods. Recently, May et al. (2010) reported a similar reduction in cigarette cravings following a brief presentation of dynamic visual noise during the image retention phase.

Simple craving reduction tasks are not limited to the visual sensory modality. Indeed, Sayette and Parrott (1999) showed that a simple olfactory task can also suppress cravings. In particular, they found that smelling a pleasant or unpleasant odour reduced smokers' cigarette cravings relative to a control water solution. More recently, we (Kemps and Tiggemann 2012) showed that a simple olfactory task involving smelling a neutral, unfamiliar aromatic substance similarly reduced cravings for food, relative to irrelevant speech and a no-task control. Thus, simple visual and olfactory tasks seem to hold real promise as a method for reducing cravings. In particular, these tasks disrupt the imagery associated with the craving and thus provide further evidence for cravings being imagery based.

20.6   Conclusions

Accumulating evidence from anecdotal reports and laboratory studies demonstrates a clear role for mental imagery in cravings. Specifically, these have shown not only that imagery can be used to induce cravings experimentally but, importantly, that it also constitutes an intervention strategy for reducing cravings. In this way, cravings are not unlike psychopathologies such as post-traumatic stress disorder, agoraphobia, body dysmorphic disorder and mood disorders, which also have a clear imagery component. Moreover, imagery-based interventions have also been used successfully in the treatment of these psychological disorders (Hackmann and Holmes 2004; Ng et al., Chap. 19). Thus the imagery basis of craving reviewed here not only contributes to the growing literature on craving but also has wider applicability to other clinical phenomena.

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Chapter 21
Clinical Applications of Motor Imagery in Rehabilitation

Francine Malouin and Carol L. Richards

Abstract This chapter first reviews motor imagery (MI) as an adjunct therapy to enhance motor function and reduce pain in neurological conditions. To help understand the results of the clinical studies investigating the effects of MI after stroke, a detailed analysis is made of studies targeting upper limb function, mobility, and locomotion. This analysis shows that although beneficial effects have been generally reported, recent conflicting results concerning improvements in upper extremity function raise methodological concerns about the specificity of MI training and the selection of outcome measures. It also revealed the need for larger controlled studies before the positive effects reported for the use of MI to enhance mobility and locomotion can be generalized. Encouraging results with the relatively new use of MI for reducing phantom limb pain and neuropathic pain are also presented. The need for assessment of MI ability before initiating training paradigms is then considered because even though MI ability is preserved in most patients with cerebral and peripheral lesions, the mental representation of actions can be weaker and highly modulated by sensorimotor inputs. The chapter concludes with reflections about the role of MI for motor skill training, the selection of patients, and MI training strategies.

Keywords Motor imagery • Mental practice • Stroke rehabilitation • Phantom limb pain • Motor functions • Motor imagery ability

F. Malouin, Ph.D. (✉) • C.L. Richards, O.C., Ph.D.
Department of Rehabilitation, Faculty of Medicine, Laval University,
Quebec City, QC, Canada

Center for Interdisciplinary Research in Rehabilitation and Social Integration (CIRRIS),
525 Boulevard Hamel East, Quebec City, QC, Canada G1M 2S8
e-mail: Francine.Malouin@rea.ulaval.ca

21.1 Introduction

Over the last 15 years the potential of mental practice (MP) through motor imagery (MI) to optimize the recovery of motor function in various fields of physical rehabilitation, and more particularly in neurorehabilitation, has created much interest. A principal advantage of using MI in therapy is that the mental rehearsal of motor tasks when and where the person is able to practice increases the number of repetitions in a safe and autonomous manner without physical fatigue. The use of MI also allows for the rehearsal of motor tasks (i.e., walking, writing) in the early rehabilitation phase when patients are unable to physically execute them (i.e., due to immobilization or paresis). In this chapter, we give an overview of the studies that investigated the effects of MP through MI when used to improve motor function in patients with a variety of neurological conditions (i.e., stroke, Parkinson's disease, spinal cord lesion) and to reduce phantom limb pain and neuropathic pain. We also examine the ability of these patients to engage in MI, as well as how MI ability can be assessed clinically. Lastly, we touch on future research directions to enable a better understanding of mechanisms underlying the therapeutic effects of MI.

21.2 MP Through MI for Retraining Motor Function

MI can be defined as an active process during which the representation of an action is internally reproduced without any overt output (Decety and Grèzes 1999), whereas MP is the repetition of imagined actions with the intention of improving its physical execution (Jackson et al. 2001). The rationale for using MI in the rehabilitation of motor impairments likely arises from the functional correlates that MI shares with the execution of physical movement. For instance, the duration of imagined movements correlates with the duration of real movements (Decety et al. 1989; Decety and Jeannerod 1995), simulation of movements evokes similar autonomic responses (Decety et al. 1991; Fusi et al. 2005; Wuyam et al. 1995), and, more importantly, the imagination of an action engages largely similar neural networks as its physical execution (Decety 1996; Lafleur et al. 2002; Malouin et al. 2003; Munzert and Zentgraf 2009). These observations suggest that real and covert movements during MI obey similar principles and share similar mechanisms.

Many of the clinical studies investigating the use of MI in rehabilitation have focused on people with sensorimotor disabilities following a stroke. Furthermore, most of these studies have involved the training of upper limb function (for reviews, see Braun et al. 2006; Dijkerman et al. 2010), while fewer have investigated the effects of MP on mobility, locomotor activities, and lower limb movements (for a review see Malouin and Richards 2010). Initially, mainly case studies, pilot and feasibility studies were reported, but recently, more randomized controlled trials (RCTs) involving a larger number of subjects have been published.

The application of MI has also been extended to promote improvements in mobility and motor function in people with Parkinson's disease (Braun et al. 2011; Tamir

et al. 2007) and spinal cord injury (Cramer et al. 2007; Grangeon et al. 2010; Popovic et al. 2011). MI has also been used in the rehabilitation of other conditions such as hand burns (Guillot et al. 2009), tendon lesions (Stenekes et al. 2009), or ankle sprain (Christakou et al. 2007).

Since 1988, a surprising number of review papers about the application of MI in rehabilitation have been published (Braun et al. 2006; Dickstein and Deutsch 2007; Dijkerman et al. 2010; Jackson et al. 2001; Malouin and Richards 2010; van Leeuwen and Inglis 1998; Warner and McNeill 1988; Zimmermann-Schlatter et al. 2008). In general, beneficial effects of MI training on motor function have been reported despite marked differences in design, training regimen, and outcome measures. However, because of several limitations and methodological bias, Braun et al. (2006), in a systematic review of selected RCT studies, stated that although there was some evidence that MP as an adjunct therapeutic intervention had positive effects on recovery of arm function, they were not able to draw definite conclusions other than that further research with a clear definition of the content of the MP and standardized outcome measurements was needed. In their overview of MI in rehabilitation, Dijkerman et al. (2010) emphasized the need to improve study designs and various methodological issues related to MI training as well as RCTs with a larger number of patients to confirm the beneficial effects of MI.

In fact, the recent publication of negative results from three large, multicenter RCTs (Bovend'Eerdt et al. 2010; Braun et al. 2010; Ietswaart et al. 2011) merits special attention. In these trials, the low compliance of therapists and patients as well as the lack of effectiveness found when attempting to integrate MI training in regular rehabilitation programs reflect the great challenge of implementing such a complex therapy (Bovend'Eerdt et al. 2010; Braun et al. 2010, 2012). In the next section, we analyze methodological aspects of the clinical studies investigating the potential of MP through MI to promote the relearning of motor function after stroke. To better understand the trends in the findings, we focused on the types of intervention, how they were implemented, and, more importantly, how the effects were assessed. Because of the very different approaches, the information is divided in two sections: studies targeting (1) upper limb function and (2) mobility and locomotion.

21.2.1   *Studies Targeting Upper Limb Function in Persons Poststroke*

Table 21.1 illustrates the results of clinical studies that share common denominators, namely, the outcome measures and the training of several upper limb tasks. The main outcome measures that have been used to evaluate the effects of mentally training activities of daily living (ADL) are the Fugl-Meyer Assessment (FMA) a clinical tool designed to globally assess sensorimotor impairment (Fugl-Meyer et al. 1975) and the Action Research Arm Test (ARAT), which assesses activity limitations of the upper extremity (Lyle 1981). In the FMA, using a 3-point ordinal scale (0, cannot

Table 21.1 Action Research Arm Test (ARAT) scores and Fugl-Meyer Assessment (FMA) scores from studies examining the effects of MI training after stroke

Study	N	Group	ARAT			FMA			TSS
			Pre	Post	Changes	Pre	Post	Changes	
Page (2000)	8	EXP	NA	NA	NA	22.1 (3.4)	30 (4.1)	7.8	1.8 yrs
	8	CTL				22.2 (4.4)	26.9 (5.4)	4.7	
Page et al. (2001a)	1	EXP	16	40	24	NA	NA	NA	5 mths
Page et al. (2001b)	8	EXP	23.5 (13.8)	40.4 (13.4)	16.4	29.1 (10.9)	43 (10.1)	13.8	2–11 mths
	5	CTL	26.4 (12.3)	25 (11.7)	−1.4	29.6 (29.4)	32.4 (14.9)	2.9	
Page et al. (2005)	6	EXP	33.1 (2.2)	43.8 (3.1)	10.7	NA	NA	NA	23 mths
	5	CTL	34.1 (1.7)	38.7 (1.2)	4.6				
Page et al. (2007)	16	EXP	18 (11)	25.8 (11.3)	7.8	33 (8.4)	39.8 (6.9)	6.7	38 mths
	16	CTL	17.3 (14.3)	17.7 (13.8)	0.4	35.8 (9.5)	36.8 (10.7)	1	45 mths
Page et al. (2009a)	10	EXP	2.9	35	5.3	35.1	38.7	4.2	3 yrs
Page et al. (2009b)	5	EXP	27.6 (1.1)	42.6 (1.2)	15.4	38.4 (1.1)	46.4 (0.9)	7.8	13–45 mths
	5	CTL	28 (1.4)	36.4 (1.1)	8.4	39.8 (1.3)	43.8 (1.1)	4.1	17–42 mths

Bovend'Eerdt et al. (2010)	15	EXP	26.9 (27.5)	31.7 (25)	4.8	NA	NA	NA	22 wks
	15	CTL	26.4 (22.6)	30.7 (23.4)	4.3				16 wks
Ietswaart et al. (2011)	39	EXP	25.6 (18.1)	31.5 (20.7)	5.9	NA	NA	NA	82 days
	31	CTL	26.2 (17.9)	32.9 (20.8)	5.3				
	32	CTL	23.1 (17.7)	30.8 (20.5)	7.3				
Page et al. (2011)	8	EXP1	24.1	26.8	2.8	31.5	34.2	2.7	
	6	EXP2	17.2	18.7	1.7	26	30	4	
	7	EXP3	25	26.8	1.8	28.7	34	5.3	36 mths
	8	CTL	24.1	24.3	0.2	31.6	33.8	2.2	

Mean and 1 SD, *EXP* experimental, *CTL* control, *TSS* time since stroke, *yrs* years, *mths* months, *NA* not available

perform; 1, can perform partially; 2, can perform fully), the evaluator grades the level of motor return through the assessment of motor synergies. A person with normal arm function would obtain a total score of 66. The ARAT is a 19-item test divided into four categories (grasp, grip, pinch, and gross movement), with the performance on each item graded on a 4-point ordinal scale (0, can perform no part of the test; 1, performs test partially; 2, completes test but takes abnormally long time or has great difficulty; 3, performs test normally), for a total possible score of 57. Although the ratings for both tests are greatly dependant on examiner judgement, both have very good psychometric properties (Duncan et al. 1983; van der Lee et al. 2001).

Table 21.1 gives the pre- and post-ARAT scores and corresponding change scores for Experimental (EXP) and Control (CTL) groups from studies using similar methodologies and outcomes. As can be seen, there is much variability in gains across studies. In the first studies, carried out in the subacute phase and with fewer subjects, gains were statistically larger in the EXP than in CTL groups (Page et al. 2001b, 2005, 2007, 2009a, b). Surprisingly, in some of these studies, there was almost no change in the ARAT scores of the CTL groups despite the conventional training received over a period of 6–10 weeks (Page et al. 2001b, 2007, 2011). In contrast, in the study wherein the CTL group received constraint-induced therapy (CIT), mean ARAT gains were 8.4, and in the corresponding EXP group who had MI training in addition to CIT, the ARAT gains were almost double (15.4) (Page et al. 2009b). These large increases in ARAT scores are in contrast with recent findings from two RCTs (Bovend'Eerdt et al. 2010; Ietswaart et al. 2011) that reported small ARAT gains (5.3–7.3) and no statistically significant difference between groups. Small ARAT gains (ranging from 1.8 to 2.8), well below the minimal clinically important difference (MCID) which is 6 points for chronic and 12 points for acute stroke (Lang et al. 2008), were also reported in a recent study comparing long (60 min) versus short (20 min) MI training sessions in persons with chronic stroke (Page et al. 2011).

21.2.1.1   Comparison of the Type and Amount of Physical Practice

How can we tentatively explain such a difference (see Table 21.1) in ARAT gains across the studies? First, let us consider the type and amount of physical practice. In the context of rehabilitation, MP is an adjunct to conventional therapy. In studies examining the effects of MI on upper limb function (Table 21.1), MI training and physical practice were delivered in separate sessions. Physical practice consisted of conventional physical and/or occupational therapy and was provided by therapists not involved in the MI training. Physical practice time varied from 30 to 60 min, 2–5 times a week, and for 2–10 weeks for an estimated total time of physical practice during conventional therapy ranging from 6 to 45 h (median of 9 h) across all studies. Moreover, the content of the physical practice training was often not specified. In some cases, it focused on the same tasks that were practiced later in a separate session with MI (Page et al. 2005, 2007, 2009a, b, 2011). From the information provided it is impossible to determine the number of movement repetitions. Thus,

the amount of time, the number of physical repetitions, and also the types of functional activities (tasks) and movements practiced varied considerably across studies and groups within studies who received interventions described as standard, usual, or conventional practice. Moreover, it is possible that the EXP group practiced more physically outside training sessions since patients apparently increase the spontaneous use of their affected arm in their ADL when they receive MI training (Page et al. 2005). The findings of the Page et al. (2009b) study that examined the effects of combining MI training with CIT, showed that ARAT scores can be quite responsive to the amount of physical practice. Indeed, in this study the CTL group, who received only CIT, which involves very intense and specific physical training of the arm, had very large ARAT gains (8.4) when compared to values near 1.0, indicating little or no effect in the CTL groups of other studies (Page et al. 2001b, 2007, 2011). It is thus reasonable to assume that the lack of control for the amount of physical practice could account for differences in ARAT scores, not only across studies but also between groups of the same study. Altogether, these observations suggest the need for a tight control of the physical practice received by patients in all groups.

21.2.1.2 Comparison of the Type and Amount of MI Training: Quantity and Quality

Two modes of delivery of MP were used in the studies reviewed (Table 21.1). One consists of listening to audiotapes describing the tasks to be rehearsed mentally (see Page and colleagues' studies, Yoo et al. 2001), and the other entails structured MP sessions either guided by a therapist (Bovend'Eerdt et al. 2010; Crosbie et al. 2004; Ietswaart et al. 2011; Liu et al. 2004) or using self-regulated practice carried out at home using written instructions (Dijkerman et al. 2004). It could also include taped scripts for home practice in addition to supervised MI training (Ietswaart et al. 2011). An audio-taped MI intervention typically consists of 5 min of relaxation asking patients to imagine themselves in a warm and relaxing place and to contract and relax muscles; this is followed by 20 min of suggestions for internal, cognitive polysensory (visual and kinesthetic cues) images related to using the affected arm in one of several (3–5) functional tasks. The tape concludes with 5 min of refocusing into the room. The trained tasks emphasize upper extremity ADL, such as reaching and grasping for a cup, using eating or writing utensils, turning pages of a book, and using a hairbrush and comb. During audio-taped delivery, the patient has to rely on a standardized script to generate mental images and sensations associated with the limb movements. In supervised sessions, however, the therapists are able to tailor the instructions to each individual and progress the exercises accordingly. The number of tasks rehearsed mentally over the training period can vary from 4 to12 across studies and commonly target more than one functional task at a time with the addition of novel tasks every week. The progression lies in the variety of tasks rather than in the refining of movement control for a given task. However, in a recent study wherein MP was integrated in the rehabilitation intervention without increasing the amount of usual therapy, MI training was used for training multiple tasks instead of concentrating on a particular

task (Bovend'Eerdt et al. 2010). In summary, numerous studies concentrated on several ecological tasks having a functional purpose. To maintain patient interest over the 2–10 weeks of training, the tasks were varied and included relatively simple gestures like reaching, or grasping an object, to more complex ADL consisting of several sequences of movements involving the whole limb or both limbs.

In contrast, fewer studies focused on the learning of a specific task such as line tracing (Yoo et al. 2001), wrist movements (Stevens et al. 2003), sequential finger movements (Müller et al. 2007), or moving tokens (Dijkerman et al. 2004). Finally, one group of researchers selected a more cognitive type of intervention instead of focusing on motor performance per se (Liu et al. 2004). Their aim was to teach the proper sequences of movement (planning) involved in 15 different tasks of progressive complexity (i.e., put clothes on a hanger and progressing to more complex activities such as going to the canteen). Subjects improved in the planning aspects of movements, but the level of motor impairment did not change, implying that different mechanisms underlie this type of imagery training (Liu et al. 2004).

Thus, as reviewed above, the content of MI training and the time dedicated to mental rehearsal as well as the estimated total time of physical practice varied greatly across studies. Importantly, the number of repetitions during the mental rehearsal portion of MI training was not monitored. As for the time spent in MI training, calculations based on the number of hours dedicated to MI indicate that it corresponded to about one third of the time spent in physical practice in the earlier studies. In recent studies, however, the time dedicated to physical and MP is about the same (Page et al. 2005, 2007, 2009a, b, 2011).

It is not enough to consider the large variability in the amount of MI training, one must also question whether the mental rehearsal was done successfully. The recent findings that an increase in the amount of MI training (comparison of 20, 40, and 60 min per session) delivered through audiotapes yielded only small ARAT gains (Page et al. 2011) point to the need to reexamine the content and mode of delivery of MI training. Furthermore, in the studies reviewed, most did not screen patients for their ability to imagine movements and second, the compliance with the mental rehearsing of complex tasks was rarely controlled. Therefore, it is not possible to determine with certainty the real dose and quality of MI training received. This is problematic since the number of repetitions in motor learning is a key factor for improvement (Allami et al. 2008; Jackson et al. 2003; Pascual-Leone et al. 1995; Reiser et al. 2011), and it has been shown that patients can underestimate up to 2–3 times the duration of complex tasks during MP (Wu et al. 2010), suggesting difficulty in representing mentally complex tasks accurately (Guillot and Collet 2005a). Moreover, when the physical and MI practice sessions are separated, the patients have to make an additional effort to remember kinesthetic sensations associated with complex functional tasks. Altogether, above observations suggest that the amount of MI training, the ability to engage in MI, and the compliance with training instructions during MI training should be controlled in future studies. Moreover, one must consider combining physical and MP within the same session to facilitate the remembrance of kinesthetic sensations and also to provide a better control of the number of repetitions so that it is easier to determine the amount of practice received.

21.2.1.3   Group Characteristics

Another factor that may help explain the disparate ARAT gains with MI training among studies is the variability in the level of functional limitations of the patients included in the studies. For instance, in the study comparing the effects of CIT with and without the addition of MI (Page et al. 2009b) that led to very large gains, the SD of the ARAT scores at baseline for both groups was very small (SD of 1.1 and 1.4, respectively) (Table 21.1), indicating that the five patients in each group who initially had a similar activity limitation responded in a similar manner and, as the change score shows, were good responders. In contrast, in the Ietswaart et al. (2011) study, the large SDs of the ARAT scores at both baseline and post-intervention in all three groups indicate a wide range in the level of activity limitation. Despite the well-controlled and intensive MI training regimen in a large sample of patients (31–39 per group) with recent stroke (mean of 82 days), the addition of MI training resulted in a small ARAT gain that was similar (nonsignificant) to those in the two control groups (a usual rehabilitation care group and an attention-placebo control group). Moreover, the ARAT gains in all three groups had a mean effect size of 0.17, and the change score was below the MCID for patients in the acute phase (Lang et al. 2008), likely reflecting responders and nonresponders. These individual effects are lost when the scores are averaged which emphasizes the need for further subgroup analyses to identify the characteristics (i.e., motor imagery ability, cognitive function) of responders and nonresponders.

21.2.1.4   Specificity of MI Training

We must also consider the need to evaluate the specific effects of MP on the recovery of movements. This leads us to try to equate what the patient practices and the sensitivity of the chosen outcome measure to that practice. An analysis of the results of the studies reported in Table 21.1 leads to the conclusion that the addition of MI training of reaching tasks used in ADL to standard therapy reduces the activity limitation in the earlier studies, but not in the more recent well-controlled RCT studies. The difference in results may be due to the choice of the ARAT (which evaluates a series of movements: pinch, grip, grasp, gross arm movement) as an outcome measure. The RCT studies evaluated the effects of MI training of several tasks, and it is not clear what the patients attain relates to movement control, be it increased muscle strength, better antagonist coordination, or intersegmental limb coordination, nor how these changes relate to the ARAT evaluation. It could also be that the training of multiple tasks reduces the size of the effect on individual tasks so that the magnitude of the effect becomes too small to be detected by the ARAT measure. In addition to the ARAT measure, some of the studies provided anecdotal examples that MI increased arm use in daily activities, but this effect was not systematically measured and compared across groups.

Very few clinical studies have examined the specificity of MP training or focused on a single task. Using quantitative outcome measures, such as the Timed Reaching computerized test, the Box and Blocks test, and the Purdue pegboard test, Crajé et al. (2010) showed that MI training of several functional activities could result in specific effects

such as improved reaching and grasping but not of fine dexterity. Such findings are of interest because they help explain the specific MI training effects on motor function. In a pilot study that controlled for compliance to the task to be imagined (mental rehearsals of sequential finger movements for 30 min/day, 5 days/week for 4 weeks), the intensive MI training led to an increase in the peak torque of the pinch grip that was comparable to that obtained with physical training, and this increase in strength was generalized to better function of the upper extremity as measured by the timed items in the Jebsen test (which assesses the time taken to execute seven upper extremity tasks) (Jebsen et al. 1969). The latter findings support the notion that a large number of repetitions of a given task can yield effects that compare to physical practice as reported earlier in healthy individuals (Jackson et al. 2003; Pascual-Leone et al. 1995). Such studies that provide a clear link between the type and intensity of MP and the effects on specific parameters of motor function based on quantitative and valid outcome measures are needed to enable the development of guidelines for MP training.

21.2.2   Studies Targeting Mobility and Locomotion in the Stroke Population

To date, studies investigating the effects of MP on walking (Dunsky et al. 2006, 2008), foot movement sequence (Jackson et al. 2004), or other tasks such as standing up and sitting down (Malouin et al. 2004a, c; Yoo and Chung 2006) have been case and feasibility studies without control groups, except for one pilot study with a small number of patients (Malouin et al. 2009a). In most studies, patients did not also receive usual therapy. When physical practice was combined to MI training within the same session, however, the number of repetitions was carefully controlled. Mental and physical repetitions were delivered in blocks in a specific ratio (i.e., one physical repetition for ten mental repetitions) and under the supervision of a therapist (Jackson et al. 2004; Malouin et al. 2004a, c, 2009a). Since the patients were requested to refrain from practicing physically the standing up and sitting down tasks outside of regular ADL activities and that the exact number of physical and mental repetitions in the EXP and CTL groups was known, it was possible to attribute the added value of MI training (1,100 repetitions) combined with a small amount (100 repetitions) of physical practice (Malouin et al. 2009a). The beneficial effects of MI for retraining mobility function are promising and need to be replicated to a larger population before assuming generalization of these effects.

The MI training was carried out under the supervision of a therapist either at home (Dunsky et al. 2006, 2008) or in a rehabilitation environment (Dickstein et al. 2004; Jackson et al. 2004; Malouin et al. 2004a, 2009a) and did not use prerecorded audiotapes. In contrast to studies on the upper extremity, in each study the training focused on one specific task, such as walking, standing up and sitting down, and a foot movement sequence. Instead of adding novel tasks along the training period, the level of difficulty entailed by the task was progressively increased. This was done, for example, by increasing the mechanical demand (standing up from a lower seat), by changing the spatiotemporal parameters (walking faster), or by increasing the number of

repetitions and the ratio between physical and mental repetitions (Malouin et al. 2004a, c, 2009a). Except for one study that examined the learning of a foot movement sequence (Jackson et al. 2004), the studies focused on improving the motor performance during a functional task related to mobility and locomotion.

Instead of assessing motor impairment and global motor function by means of clinical tests with ordinal scales, outcome measures specific to the nature of the task trained were used to assess the effects of MP on mobility and walking performance. For the standing up and sitting down tasks, the amount of loading of the paretic limb was assessed using vertical forces recorded with two force plates (Malouin et al. 2004a, 2009a) or with a limb load monitor in the case study reported by Yoo and Chung (2006). In a feasibility study (Malouin et al. 2004a), limb loading was found to be a more sensitive variable than movement time to assess whether the patients had learned the new motor strategy that aimed at increasing the vertical force exerted with the affected side instead of standing up faster by overloading the good side. All three studies confirmed that the patients learned to increase the load on their more affected leg (>15% increase) during standing and sitting down after MI training alone (Yoo and Chung 2006) or combined with a small amount of physical practice (Malouin et al. 2004a, 2009a) and that the effects were maintained at follow-up (Malouin et al. 2009a). The ability to engage in MI and/or cognitive status were also screened in many of these studies (Dickstein et al. 2004; Dunsky et al. 2006, 2008; Jackson et al. 2004; Malouin et al. 2004a, c, 2009a), and mental chronometry (duration of imagined tasks) was used to gauge engagement in imagery training (Dickstein et al. 2004; Dunsky et al. 2006, 2008; Malouin et al. 2004a, c, 2009a; Jackson et al. 2004).

In a series of studies, Dickstein and colleagues investigated the effects of a home MI training program on walking. The effects of the program on walking performance were assessed using spatiotemporal (gait speed, cadence, symmetry, etc.) and kinematic (knee and ankle amplitude) parameters (Dickstein et al. 2004; Dunsky et al. 2006, 2008). Most patients increased their gait speed with gains ranging from about 10 to 80% (mean 40%), resulting in a mean increase of 15 cm/s. The effect size was 0.64 (Dunsky et al. 2008), corresponding to a moderate treatment effect, and most of the gains were retained at follow-up 3 weeks after the end of training, creating interest because it supports the idea that walking skills can be enhanced by MP. The studies on the effects of MI training on locomotion, however, did not include a control group, and also the amount of walking outside of the therapy sessions was not monitored during the 6-week intervention. Further studies with control groups and with a better control of walking activities during the training program are needed to estimate the real contribution of MI training to the reported gains.

21.3   Studies of MI Training in Parkinson's Disease

Two recent studies have examined the potential of MP to promote motor function recovery in people with Parkinson Disease (PD). The fact that the group of patients who combined physical and MP over a 12-week period performed various mobility

tasks faster than the group who trained physically only provided evidence that MP could help in reducing bradykinesia (Tamir et al. 2007). Unfortunately, these results were not confirmed in a subsequent study comparing the effects of MP and relaxation integrated into usual physiotherapy interventions on mobility and gait in persons with PD (Braun et al. 2011). The small changes observed in both groups in Braun et al.'s study may be related to a combination of more severely affected participants (Hoehn and Yahr greater than 3) and less intensive MI training. MI training for 20 min was embedded in the 6 total hours of regular therapy interventions over 6 weeks for a total of 2 h, whereas in the Tamir et al. (2007) study the patients received 40 min, twice a week for 12 weeks for a total MI intervention of 16 h. The inclusion of a third group with physical therapy alone would have been useful to determine the added value of relaxation and MP.

These findings further support the need to provide a sufficient amount of practice to obtain improvement of motor performance and underline the necessity of monitoring compliance in engaging in MI, as well as the need to control for the amount of physical training received by patients within and outside training sessions. Another factor that may affect the response to MP training in PD is an underlying impairment of the imagery process (Frak et al. 2004; Lee et al. 1998). Yaguez et al. (1999) compared the ability to learn grapho-motor trajectories by means of a 10-min training period using MI in a group of patients with PD to that of a group of patients with Huntington's disease (HD). Their results showed that MP helped the performance of patients with HD, but not that of those with PD. It was further demonstrated that patients with PD did not learn the task with physical practice and, in addition, did not perform well on measures of visual imagery. Thus, these findings suggest that damage to subcortical structures may reduce the ability to produce the appropriate imagery process and again emphasizes the importance of assessing the MI ability of patients before considering using MI training.

21.4   Studies Using MI Training in Spinal Cord Injury

The use of MI for training motor function in persons with spinal cord injury (SCI) is relatively new, and to date studies have targeted mainly upper limb function. Positive results from one case study describing the use of MP to retrain elbow extension following tendon transfer in a young woman with tetraplegia are encouraging (Grangeon et al. 2010). Imagination of movement prior to real movement combined with functional electrical stimulation has also been used to improve voluntary grasping among individuals with tetraplegia secondary to traumatic SCI (Popovic et al. 2011). Applications to locomotor function in incomplete SCI should also be possible since the representation of foot movements is retained even in persons with complete SCI (Alkadhi et al. 2005; Cramer et al. 2007; Hotz-Boendermaker et al. 2008). A possible limitation to the use of MI in persons with complete SCI is the

exacerbation of neuropathic pain described in some patients (Gustin et al. 2008) when MI involves muscle groups below the lesion level (see Sect. 21.5.2).

21.5 MI for Reducing Pain

21.5.1 MI for Phantom Limb Pain After Limb Amputation

Phantom limb pain (PLP) which affects 60–80% of amputees remains a clinical enigma that is difficult to treat (Flor 2002). After the amputation of a hand, the representation of the body parts adjacent to the hand in the cortical somatotopy expands in the motor and sensory cortices, with the size of the expansion apparently associated with the severity of the pain (Flor et al. 1995), thus suggesting that PLP results from maladaptive plasticity (Grusser et al. 2001; Lotze et al. 2001). Furthermore, Birbaumer et al. (1997) reported that the S1 reorganization associated with phantom limb pain could be reversed within 20 min following the elimination of pain by regional anesthetic blockade supporting the idea that cortical reorganization following deafferentation results at least partly from mechanisms that can be rapidly reversed. These findings led to the development of different ways of stimulating the motor and sensory cortices. Moseley (2006) demonstrated significant pain relief in patients with complex regional pain syndrome (CRPS) and PLP when they first learned to improve laterality recognition using photographs of their hands in varying positions and then learned to imagine the injured hand in non-painful postures (graded MI). Mirror therapy has also been reported to have an analgesic effect in PLP (Chan et al. 2007). Findings from a recent study combining fMRI and behavioral assessment in 13 upper limb amputees (MacIver et al. 2008) revealed a significant reduction in intensity and unpleasantness of constant pain and exacerbations that was associated with the elimination of cortical reorganization following MI training. Their findings add to our current understanding of the pathophysiology of PLP, underlining the reversibility of neuroplastic changes in this patient population while offering a novel, simple method of pain relief.

In another study with a single case multiple baseline design, MI training was combined with observation to reduce PLP in six people with upper and lower limb amputation (Beaumont et al. 2011). Four participants reported a reduction of pain greater than 30% from baseline at the end of the 8-week program (4 weeks with supervision and 4 weeks at home). Group analyses confirmed that average pain levels were lower after intervention than at baseline and had returned to baseline after 6 months. Altogether these studies provided evidence that stimulating the motor and sensory cortices in different ways can help relieve PLP and that persons with PLP may benefit from these novel interventions alone or in combination. But not all patients react in the same way, and in some, the neuropathic pain may increase (see Moseley 2004; Moseley et al. 2008).

21.5.2   MI for Neuropathic Pain After SCI

Approximately one-third of all people with a SCI develop neuropathic pain below the lesion level (Siddall et al. 2003). Of all the possible pain types, below-level neuropathic pain is the most likely type of SCI pain to be described as severe or excruciating. In a recent investigation, Wrigley et al. (2009) found that subjects with complete SCI and below-level neuropathic pain had a reorganization of the primary somatosensory cortex that correlated with pain intensity, thus providing further evidence of a link between the degree of cortical reorganization and the intensity of persistent neuropathic pain. Fewer studies have examined the effects of MI to alleviate neuropathic pain after SCI. In a pilot study, Moseley (2007) used a visual illusion paradigm to reduce neuropathic pain in five persons with paraplegia. He experimented with three conditions: (a) virtual walking: He ingeniously placed a mirror in front of a screen so that the patients observed a film of lower body walking. He then asked them to align their upper body to the walking lower body then to imagine walking and to observe themselves walking; (b) guided MI; (c) watching a film (control). While one patient withdrew from virtual walking because of distress, the four others had mean decreases in pain of 65 and 25% with the virtual walking and MI conditions, respectively, as compared to 6% for the control condition. These positive effects were not supported in another study (Gustin et al. 2008) that examined whether neuropathic SCI pain could be modified by imagined movements of the foot. Fifteen persons with a complete thoracic SCI (seven with below-level neuropathic pain and eight without pain) practiced MI three times daily for 7 days. Six out of seven subjects with neuropathic pain reported an increase in pain during imagined movements, and in SCI subjects without neuropathic pain, MI evoked an increase in non-painful sensation. This study reports exacerbation of pain in response to imagined movements, and it contrasts with reports of pain reduction in people with peripheral neuropathic pain. The use of MI in pain control in SCI is a new and evolving area of research. The recent identification of central neural circuits associated with the induction of pain during movement imagery after complete SCI (Gustin et al. 2010) may lead to a better understanding of this phenomenon.

21.6   MI Ability After Cerebral and Peripheral Lesions

21.6.1   MI Ability After Stroke

The ability to form internal representations of motor acts is necessary for MI training, hence the need to determine whether this ability is affected following lesions of the central (CNS) or peripheral (PNS) nervous system. Because of its concealed nature, however, MI needs to be assessed through different strategies. Although several sophisticated approaches exist for assessing MI ability (Collet et al. 2011;

Guillot and Collet 2005b; Heremans et al. 2008), three main approaches have been used to assess MI ability in clinical settings: mental rotation (Johnson 2000; Johnson et al. 2002), mental chronometry (Decety and Boisson 1990; Malouin et al. 2008a; Sirigu et al. 1995; Stinear et al. 2007), and questionnaires (Malouin et al. 2007, 2008b). To date, studies have shown that in most cases, MI ability is maintained after cerebral lesions (Johnson 2000; Johnson et al. 2002; Malouin et al. 2008b). Studies investigating the accuracy of MI (mental rotation) concluded that the representation of movement remains possible after stroke, even in chronic patients with severe motor impairments (Johnson 2000; Johnson et al. 2002). This suggests that following CNS injury the mental representation of movement is not dependent on motor activity. Other studies in patients with stroke and age-matched healthy subjects who were assessed with the Kinesthetic and Visual Imagery Questionnaire (Malouin et al. 2008b) revealed that the level of MI vividness (clarity of images and intensity of sensations) following stroke was similar to that of healthy subjects, with good and bad imagers in both groups. However, a few cases of patients with impairments of MI (accuracy and temporal congruence) have been described following focalized lesions in the superior region of the parietal cortex (Sirigu et al. 1996) or the frontal cortex (Johnson 2000). Patients with a right hemispheric lesion are also more susceptible to show a slowing of MI (Malouin et al. 2004b, 2012; Stinear et al. 2007). Indeed, a recent study (Malouin et al. 2012) reported that patients with a right hemispheric lesion ($n = 19$) had longer movement times during the imagination than during the physical execution of stepping movements; moreover, the slowing of MI was observed in patients with extensive right cerebral lesions. In contrast, patients having a left hemispheric stroke ($n = 18$), like the age-matched control group, showed a temporal congruence between imagination and execution times (Malouin et al. 2012). Altogether these observations support the need for the evaluation of MI ability especially after a right hemispheric lesion. This can be done by means of simple clinical tools easily available to therapists, a MI questionnaire for assessing MI vividness, and mental chronometry to examine temporal organization of MI (Malouin et al. 2008b).

21.6.2 *MI Ability After SCI*

Evidence that the representation of foot movements is retained in persons with complete SCI has been confirmed in behavioral (Decety and Boisson 1990) and fMRI studies. For example, scores of MI vividness after complete SCI are similar to those of controls, and the extent of brain activation during imagery of foot movements correlates with the vividness of their imagery (Alkadhi et al. 2005; Cramer et al. 2007; Hotz-Boendermaker et al. 2008). The preservation of motor representations in the disconnected limbs after a complete SCI further supports the notion that MI is maintained even when voluntary movements are not possible (Johnson et al. 2002).

21.6.3   MI Ability in PD

As mentioned above in Sect. 21.3, difficulty in visual imagery has been detected in patients with PD (Lee et al. 1998; Yaguez et al. 1999). In another study comparing MI accuracy during a grasping task in eight patients with PD (stage 3 Hoehn and Yahr) with age-matched controls (Frak et al. 2004), the patients did not perform as well as their counterparts in judging the orientation of simulated grasp movements. A more recent study compared several domains of MI ability in 14 patients with PD (stage 1–3 Hoehn and Yahr) with an age-matched control group. Using an extensive imagery ability assessment battery, Heremans et al. (2011) reported that patients performed imagery tasks more slowly than controls, but that in most patients, vividness and accuracy were well preserved. Another study reported a good stability of MI vividness scores (KVIQ) measured 5–7 days apart, thus confirming the reliability of the KVIQ for testing MI vividness in this population (Randhawa et al. 2010). Altogether these results suggest that MI vividness is generally well preserved in PD, but that in the more advanced stages of PD, the accuracy and temporal organization of MI may show signs of impairment.

21.6.4   MI Ability After Amputation and Immobilization

After the loss of a limb (Malouin et al. 2009b; Nico et al. 2004) or temporary disuse following limb immobilization (Malouin et al. 2009b), MI ability is modified by the lack of movement. For instance, while the representation of movements is possible after upper limb amputation, the accuracy during a left/right hand judgment task is decreased, suggesting that after the loss of a limb, MI is more difficult (Nico et al. 2004). Likewise, MI vividness after lower limb amputation was significantly decreased for foot movements of the missing limb, indicating that the vividness of the imagined actions is weaker after the loss of a limb (Malouin et al. 2009b). Similar changes of MI vividness during simulation of movement by the immobilized limb have been reported in subjects who had an ankle immobilized in a cast for 2–4 weeks without weight bearing (Malouin et al. 2009b). Overall, these findings indicate that after limb amputation and disuse, the mental representation of actions is retained but is weaker and highly modulated by sensorimotor inputs.

21.7   Conclusions and Future Research Directions

21.7.1   The Role of MI for Motor Skill Training

The priming effect of MI on physical performance is fundamental (Pascual-Leone et al. 1995). A general principle is that the same number of physical repetitions will produce

a greater effect than MI training alone and that the addition of MP can enhance the effects of physical practice. Thus, when trying to elucidate the role of MP, the addition of a small number of mental repetitions in an experimental group, especially when the MI and physical practice are carried out separately, will not be enough to make a difference if compared to a control group engaged in an equivalent amount of physical practice because physical training will always yield greater gains. Therefore, we have to seek paradigms combining a large number of mental repetitions to a small amount of physical repetitions (well controlled in terms of number) to confirm the added value of MI training while controlling for the compliance of patients to engage in MI (Malouin et al. 2009a). The use of mental repetitions should optimize the effects of physical practice and also reduce the number of physical repetitions required to attain the same results.

We also have to determine whether motor recovery can be enhanced by MI training alone. In addition to optimizing physical practice as mentioned above, its use in patients unable to physically practice movements should theoretically help keep the sensorimotor circuitry functional and promote faster recovery once physical practice becomes possible or, in the case of SCI, help maintain the cortical representation of movements. We know that MI training alone can promote both the learning of a task and the priming of physical practice but that this entails hundreds of mental repetitions (Pascual-Leone et al. 1995; Jackson et al. 2003; Allami et al. 2008; Reiser et al. 2011). The demand for such intensity makes it difficult to successfully train several motor skills simultaneously and would require focusing on one task at a time as athletes do.

21.7.2 The Selection of Patients

Screening for cognitive problems and MI ability should be mandatory (Malouin et al. 2004c). Reduced working memory and attention skills can make the teaching of MI more difficult (Braun et al. 2010). Older subjects without previous exposure to MI may also be less positive and less readily able to engage in these demanding and abstract procedures. Therapists recognize that teaching MI and controlling for compliance of the patients are hard in older and frail persons, leading to longer instruction times and some irritation and uncertainty (Braun et al. 2010). Implementation of MI in regular therapy has proven quite difficult so far (Bovend'Eerdt et al. 2010; Braun et al. 2010), suggesting that as for other adjunct therapies, MI training may not be suitable for all patients, nor indicated for all phases of rehabilitation. Further subgroup analyses are needed to identify the characteristics of responders and nonresponders instead of concentrating only on group averages and statistics.

21.7.3 The Training of MI

There is a need to compare different approaches to the teaching and practice of MI, to examine how they complement each other to better understand their respective

advantages, and to identify the characteristics of people who will benefit most from the intervention (responders). For instance, while both visual cues and auditory cues can facilitate motor responses during MI of hand muscles, older persons have been shown to respond better to auditory cues (Hovington and Brouwer 2010). Recent findings that therapeutic effects of MI training on walking performance were further enhanced by using kinesthetic instead of visual imagery and that greater positive effects were obtained by adding an auditory step rhythm is another example of how to guide the development of MI training strategies (Kim et al. 2011). Finally, studies that provide a clear link between the type and intensity of MI and effects on specific parameters of motor function based on quantitative and valid outcome measures are needed to enable the development of guidelines for MP training.

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Chapter 22
Summary and Some Future Directions

Rebecca Lawson and Simon Lacey

Keywords Imagery • Unisensory • Multisensory • Crossmodal • Applied imagery • Rehabilitation

22.1 Summary

In this final chapter, we draw together some of the themes that have emerged during the course of the book and highlight areas of interest for further research. These include working to clearly define crossmodal and multisensory imagery, their relationship to synaesthesia and hallucinations, the evidence for the functional equivalence of imagery and perception that is now emerging from all the senses, the exploitation of advanced neuroimaging techniques, and recent developments in therapeutic and rehabilitative applications of imagery.

22.2 Definitions and Distinctions

We noted in the Introduction that the title of this book, "Multisensory Imagery", was something of a flag of convenience, covering not only unisensory imagery across all the sensory modalities but also crossmodal interactions between different modalities involving imagery, and imagery that is more strictly multisensory. Defining unisensory imagery is straightforward, but the other two are more nuanced.

R. Lawson (✉)
School of Psychology, University of Liverpool, Liverpool, UK
e-mail: rlawson@liv.ac.uk

S. Lacey
Department of Neurology, Emory University School of Medicine, Atlanta, GA, USA

Spence and Deroy (Chap. 9) offer a detailed analysis of crossmodal imagery, defining this as the generation of a mental image in one modality in response to either a perceived or imagined stimulus in another modality. They identify four classes of such crossmodal imagery: (1) "immediate", when imagery is directly triggered by stimulation in another modality, for example visual images of an object triggered by touching it; (2) "mediated", which occurs after input from another modality has been categorized as specifying a particular kind of imagery, for example when visually recognizing lip movements as speech related then induces auditory imagery; (3) "crossmodal spreading", when an image in one modality triggers imagery in another, for example a visual image of food triggering an olfactory or gustatory image; and finally (4) "crossmodally induced top-down imagery", when images arise in response to thoughts or concepts, provided that there is some necessary and specific sensory connection between the two.

Definitions of multisensory imagery are perhaps harder to pin down. An image could be multisensory in the sense that it is derived from multiple modalities. For example, Loomis et al. (Chap. 8) discuss how spatial images derived from vision, touch and audition are involved in navigation and interacting with the environment. In addition, Lacey and Sathian (Chap. 11) discuss the evidence for a multisensory object representation that can be encoded and retrieved by vision and touch in the context of object processing. Imagery might also be multisensory if there is simultaneous activation of related unisensory images, for example the sight, taste and smell of food, together with information about texture or "mouthfeel", and even auditory imagery, like the crunch of an apple. However, even though we might experience such imagery as multisensory, as Spence and Deroy point out in Chap. 9, it might be no more than a rapid switching between separate, unisensory images.

Further definitional issues arise in distinguishing imagery from synaesthesia as discussed by Spence and Deroy (Chap. 9) and Craver-Lemley and Reeves (Chap. 10). Criteria to differentiate mental imagery from synaesthesia include vividness, the degree of automaticity and lack of voluntary control over the experience as well as the difficulty in transforming internal representations, all of which tend to be higher for synaesthesia than for imagery. In addition, crossmodal imagery is usually similar across people whereas synaesthetic experiences are typically extremely idiosyncratic, albeit consistent over time for a given person. Finally, mental imagery is almost universal whereas synaesthesia is relatively rare. On this basis, Craver-Lemley and Reeves argue that synaesthesia is a separate mental class, distinct from imagery. On the other hand, the differences between crossmodal imagery and synaesthesia may be relative rather than absolute. In a case study of vision-touch synaesthesia, Blakemore et al. (2005) reported that, on observing touch, their synaesthete showed similar areas of activation (in the somatosensory cortex, premotor and parietal cortices) to non-synaesthetes. However, somatosensory and premotor activity was greater for the synaesthete, and only the synaesthete had a concurrent, conscious tactile experience. This suggests that overactivity in the neural system that responds to observing touch may be at the root of synaesthetic experiences in this case.

A second distinction that is commonly made is between imagery and hallucination. Both phenomena involve quasi-perceptual experiences in the absence of the appropriate sensory input, and both can involve any one modality as well as multiple modalities simultaneously. Gallace (Chap. 3) and Hubbard (Chap. 4) discuss tactile and auditory hallucinations, respectively, and there is a large literature on visual hallucinations. Olfactory hallucinations occur in headache disorders (Coleman et al. 2011) and Parkinson's disease (Bannier et al. 2012), as well as schizophrenia (Arguedas et al. 2012) and gustatory hallucinations have also been reported (Lewandowski et al. 2009; Kroemer and Kawohl 2011). Hallucinations are typically distinguished from imagery by being involuntary and mistakenly attributed to an external source (see Gallace in Chap. 3). Nevertheless, this distinction may not be clear cut: interestingly, Parkinson's patients identified their olfactory experiences as hallucinations (Bannier et al. 2012), so although they were involuntary, they were not misattributed, which may raise questions about the definition of hallucinations. It may be more appropriate to consider mental images and hallucinations as lying on a continuum than as being entirely separate experiences.

22.3 Functional Equivalence of Imagery and Perception

The functional equivalence hypothesis suggests that images share many characteristics with actual percepts and that the brain treats these as qualitatively equivalent (Finke 1980).[1] This hypothesis is supported by behavioural evidence from a number of modalities. Visual imagery studies of mental scanning and rotation, for example, show a linear relationship between response times and the distance to be scanned and angular disparity (see Kosslyn 1980, 1994) in the same way that would occur if one were actually scanning a real scene or rotating a real object. By the same token, silent readers take longer to respond to words containing long vowels than short vowels, so they behave in a similar way as if they were reading aloud (Abramson and Goldinger 1997), and Hubbard (Chap. 4) reviews a wealth of evidence that auditory imagery preserves acoustic properties of perceived auditory stimuli, such as pitch, loudness and timbre. While visual and auditory imagery provide the bulk of the behavioural evidence, Bensafi et al. (Chap. 5) note that olfactory imagery preserves information about the intensity and concentration of perceived odours, and Anema and Dijkerman (Chap. 6) review similarities between motor imagery and actual performance. People may also behave similarly during perception and imagery: for example, eye movements are similar in vision and visual imagery (Bourlon et al. 2011), sniffing occurs more during both olfaction and olfactory imagery (Bensafi et al. 2003) and heart rate and respiration increase during imagined locomotion

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[1] Note that Loomis and colleagues (Chap. 8) use "functional equivalence" in a different sense, referring not to a relationship between imagery and perception, but to a relationship between images derived from inputs from different modalities.

(Decety and Jeannerod 1996). However, these similarities are not always observed. For example, salivation only appears to increase as a result of perceiving a taste and not due to taste imagery (Drummond 1995).

However, as discussed in the Introduction, many such studies have been criticized for their susceptibility to experimenter expectancies and/or their reliance on introspective self-report. With the rise of neuroimaging methods (reviewed by Ganis and Schendan in Chap. 15), considerable effort has gone into establishing objective support for the claim that functional equivalence arises from a common neural basis for imagery and perception in each modality. As a result, there is now substantial evidence for common neural areas in visual and auditory imagery and perception, as reviewed by Ganis (Chap. 2) and Hubbard (Chap. 4), respectively, and the other sensory modalities are following suit. Anema and Dijkerman (Chap. 6) review the extensive evidence for a common motor network involved in both imagery and performance of an action. Likewise, Bensafi et al. review the activation of both primary and secondary cortex for both olfactory and gustatory imagery in Chap. 5, although as yet relatively few studies have addressed this issue in these modalities. As noted by Gallace in Chap. 3, the neural basis of tactile and haptic imagery is perhaps the least explored of all.

One question addressed by several chapters is the extent to which primary cortical areas for a given modality are activated during imagery. Ganis argues strongly that primary visual cortex is functionally involved in visual imagery (Chap. 2). However, in Chap. 13, Bartolomeo et al. review a number of patient studies and conclude that visual occipital areas are not necessarily involved in imagery since damage to these areas is not always associated with visual imagery deficits. By contrast, they argue, damage to the motor network invariably results in motor imagery deficits (see also Anema and Dijkerman, Chap. 6). In addition, there may be little or no role for primary auditory cortex in auditory imagery as discussed by Hubbard in Chap. 4. Clearly there is more work to be done in determining whether, and why, primary sensory cortex is involved in imagery in some modalities but not others and to further delineate the relationships between sensory cortices and imagery. A further important goal for future research will be to determine the extent to which systems are shared across perception and imagery for different modalities (see, for example, Daselaar et al. (2010) for cortical areas common to visual and auditory imagery).

22.4   Methodology

Of the many neuroimaging techniques reviewed by Ganis and Schendan (Chap. 15), perhaps the most intriguing is multi-voxel pattern analysis (MVPA). Many studies have now shown that mental content can be decoded from neural activity using MVPA (see Tong and Pratte (2012) for a review), and these techniques have recently been applied to the case of crossmodal imagery. Viewing silent videos that implied sound (e.g. watching a violin being played) was accompanied by auditory imagery of the implied sound and MVPA of activity in auditory cortex predicted not only the category of the sound but also the exemplar within that category (Meyer et al. 2010).

In addition, when watching videos of haptic exploration of familiar objects by human hands, activity in primary somatosensory cortex predicted which object had been seen (Meyer et al. 2011). MVPA clearly holds promise for investigating other crossmodal combinations and for probing other aspects of multisensory and cross-modal imagery.

Recent advances have gone beyond simple MVPA and enabled reconstructions of mental content to be externalized. For example, Nishimoto et al. (2011) trained a pattern classifier with a vast bank of video clips and showed that dynamic brain activity while viewing other clips could be converted into video reconstructions. Similarly, Pasley et al. (2012) reconstructed speech sounds such that individual words could be decoded by a speech recognition algorithm. These techniques are undoubtedly in their infancy, and the reconstructions are by no means perfect. Pasley et al. (2012) point out that although their algorithm could identify words, the recon-structed speech sounds were not always clearly intelligible to the human ear. Nonetheless, these studies are a powerful proof of concept and offer many potential applications (see Sect. 22.6 below).

22.5 Individual Differences

A number of interesting questions concerning individual differences arise from the chapters in this book. Although the imagery literature is dominated by visual imag-ery, there is little evidence that this is actually people's preferred imagery modality, and there may be wide individual differences as to the modality in which people are most proficient at imagery. Preferences for visual object and spatial imagery, as reviewed by Kozhevnikov and Blazhenkova in Chap. 16, have their counterparts in haptic and multisensory representations as discussed by Lacey and Sathian in Chap. 11. But we do not know whether these preferences are stable across modalities such that, for example, individuals who are visual spatial imagers are usually also haptic spatial imagers.

Where individual differences in imagery have been investigated in non-visual modalities, the tendency has been to follow the visual imagery literature in using vividness as an index of imagery ability. However, as we discuss in Chap. 14, the assumption that more vivid imagery reflects greater imagery ability is not warranted in visual imagery (see also Kosslyn et al. 1984) and may be similarly unsupported in the other modalities. Assessing imagery ability requires instruments that tap the underlying processes, and while some of these may apply equally to all modalities, for example generation and maintenance, others may have modality-specific aspects, for instance image transformation may involve spatial transformation in visual or haptic imagery but temporal transformation in auditory imagery.

Understanding individual differences is not just theoretically important: it may also improve the effectiveness of imagery interventions. Tailoring an imagery strat-egy or therapy to an individual's preference for object or spatial imagery and to their preferred imagery modality is likely to yield better results than pursuing a

"one-size-fits-all" approach. Where such a "bespoke" approach is impractical, a further question is raised about the malleability of individual preferences and whether these can be altered and improved by training.

22.6   Applications

We have already hinted in our discussion of imagery and hallucinations that imagery might have a dark side. Intrusive and unwanted imagery can be upsetting and annoying at best: we have probably all experienced the irritating tune that we cannot get out of our heads or "earworms" discussed by Hubbard (Chap. 4) and negative imagery may be implicated in insomnia (Nelson and Harvey 2003). At worst, such imagery can be maladaptive and pathological: Ng et al. (Chap. 19) discuss how unwanted imagery of traumatic events contributes to post-traumatic stress disorder and the role of prospective imagery of future events, positive and negative, in bipolar disorder. Nonetheless, imagery has long been acknowledged as an important rehabilitative and therapeutic strategy. Malouin and Richards review how motor imagery and mental practice may improve function following stroke or for those with Parkinson's disease or phantom limb pain (Chap. 21), and both Ng et al. (Chap. 19) and Kemps and Tiggeman (Chap. 20) show that the negative effects of imagery may be treated using relatively simple imagery interventions to suppress maladaptive images or to replace them with more positive images. Further afield than the areas covered in this book, imagery interventions have been effective in reducing gambling behaviours (Whiting and Dixon 2012) and sleep disturbances such as nightmares in veterans and the general population (see Long et al. 2011) and increasing prospective memory function after traumatic brain injury (Potvin et al. 2011).

In Chap. 13, Bartolomeo et al. raised the intriguing possibility of using a combination of imagery and neuroimaging to assess levels of consciousness and to communicate with patients with complete or near-complete paralysis of voluntary movements. Recent work has brought this closer to fruition. Pasley et al. (2012) suggest that once MVPA techniques for decoding the content of auditory imagery of speech (see Sect. 22.4 above) are sufficiently advanced, they could be used in brain–computer interfaces for communication, for example with locked-in syndrome patients (see Tong and Pratte (2012) for a brief discussion of the ethical and legal issues related to MVPA applications that will likely also apply to other forms of decoding). Other brain–computer interfaces decode signals from implanted microelectrode arrays, typically in motor cortex, in order to control other devices, for example a cursor (Simeral et al. 2011) or a robotic arm (Hochberg et al. 2012). To the extent that these signals arise from imagery, these may represent the most exciting development in applied imagery. Although motor imagery might be the most obvious choice for such interventions, auditory imagery has also given positive results (Felton et al. 2007) raising further questions about crossmodal aspects of imagery.

22.7 Conclusions

Our relatively deep understanding of visual imagery has, to some extent, guided research into imagery in the non-visual modalities. An important goal is to model imagery in these modalities to this same level of detail whilst having due regard to modality-specific aspects of non-visual imagery, as Gallace points out in Chap. 3. An important component of this research goal will be to achieve a better understanding of individual differences in imagery across modalities. A related aim is to increase the range and effectiveness of imagery interventions, from simple behavioural strategies to technically complex applications involving brain–computer interfaces.

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