Juan C. Castro-Alonso *Editor*

Visuospatial Processing for Education in Health and Natural Sciences

Springer

Visuospatial Processing for Education in Health and Natural Sciences

Juan C. Castro-Alonso
Editor

Visuospatial Processing for Education in Health and Natural Sciences

Springer

Editor
Juan C. Castro-Alonso
Center for Advanced Research in Education
Universidad de Chile
Santiago, Chile

ISBN 978-3-030-20968-1 ISBN 978-3-030-20969-8 (eBook)
https://doi.org/10.1007/978-3-030-20969-8

© Springer Nature Switzerland AG 2019
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To my dearest Carlotita, and our Lucas,
Antonia, and Benjamin;
they give me new meanings for visuospatial
processing and life.
To my parents, pivotal in all my academic
and general efforts.
To our STEM Group and collaborators at
Universidad de Chile.

Contents

Chapter 1
Overview of Visuospatial Processing for Education in Health and Natural Sciences

Juan C. Castro-Alonso

Visuospatial processing can be defined as the ability of working memory to generate and transform visual and spatial information, presented as both static and dynamic displays (see McGrew 2009; Ness et al. 2017). This ability is a key asset to study and understand concepts of the health and natural sciences disciplines (e.g., Wai and Kell 2017), as these fields use visual and spatial resources for explanation and communication (see Mathewson 2005). Because these disciplines are more visuospatially demanding at the university than at the school level (see Oliver-Hoyo and Babilonia-Rosa 2017), the focus of this book is on university students learning about health and natural sciences.

The goal of this first chapter is to provide a brief overview of the chapters of this volume, in which I had the privilege and honor of being a coauthor with leading international researchers in educational psychology, science learning, and visuospatial processing.

1.1 Organization of This Volume

The following sections, which describe the other seven chapters of this volume, obey this similar structure:

- a table showing the main structure of the chapter;
- a text summarizing the main themes per chapter; and
- a *wordcloud* (generated in Wordclouds.com) depicting the most frequent words selected per chapter.

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_1

1.1.1 Chapter 2 – Different Abilities Controlled by Visuospatial Processing

The structure of Chap. 2 is shown in Table 1.1.

In Chap. 2, Castro-Alonso and Atit (this volume) review several abilities controlled by the visuospatial processor, one of the systems in the multicomponent model of working memory by Baddeley and Hitch (1974; see Baddeley 1992). As a relatively independent component, the visuospatial processor tends to process information separately from the other components (e.g., the verbal processor, see Bruyer and Scailquin 1998; Shah and Miyake 1996).

The scale of the visuospatial information that this component manages allows a dichotomic categorization between (a) environmental or *large-scale spatial abilities*, and (b) object or *small-scale spatial abilities* (see Hegarty and Waller 2004; Kozhevnikov and Hegarty 2001). The focus of Chap. 2 (and this volume) is on the abilities most investigated in health and natural science education, namely, the small-scale abilities (e.g., Castro-Alonso and Uttal 2019; Wai et al. 2009).

Small-scale visuospatial processing abilities can also be subdivided into two groups, according to research traditions. One tradition has typically investigated pen-and-paper *spatial ability tests* (e.g., Michael et al. 1957). The other research tradition has employed visuospatial stimuli for *working memory tasks* (e.g., Milner 1971). As both types of tasks are processed by the same subcomponent of working memory, they usually show significant interactions and correlations (e.g., Miyake et al. 2001; Stericker and LeVesconte 1982; Vandenberg and Kuse 1978).

From the tradition of spatial ability research, the abilities described include *mental rotation*, in both three-dimensional and two-dimensional forms (e.g., Castro-Alonso et al. 2014; Fiorella and Mayer 2017; Shepard and Metzler 1971; Stull et al. 2018a), *mental folding* or spatial visualization (e.g., Atit et al. 2013; Eitel et al. 2019; Pilegard and Mayer 2018; Shepard and Feng 1972), and *field independence* (e.g., Berney et al. 2015; Stericker and LeVesconte 1982; Wiegmann et al. 1992).

From the tradition of working memory research, the tasks include *spatial working memory* (e.g., Castro-Alonso et al. 2018b; Lejbak et al. 2011; Smirni et al. 1983; Wong et al. 2018), *visual working memory* (e.g., Blacker et al. 2014; Hammond et al. 2019; Wilson et al. 1987), and *dual tasks of working memory* (e.g., Foster et al. 2017; Minear et al. 2016; Örün and Akbulut 2019).

Table 1.1 Structure of Chap. 2

Section
Visuospatial Processing by Working Memory
Two Scales of Visuospatial Processing
Small-Scale Visuospatial Processing Abilities
Interactions Between Visuospatial Processing Abilities
Discussion

Several of the instruments to measure these diverse tasks are the Mental Rotations Test (e.g., Peters et al. 1995), Card Rotations Test (e.g., Sanchez 2012), Paper Folding Test (e.g., Ekstrom et al. 1976), Hidden Figures Test (e.g., Gold et al. 2018), Corsi Block Tapping Test (e.g., Milner 1971), Spatial N-Back Task (e.g., Kirchner 1958), Visual Patterns Test (e.g., Della Sala et al. 1999), Object Location Memory (e.g., Eals and Silverman 1994), Rotation Span (e.g., Shah and Miyake 1996), and Symmetry Span (e.g., Kane et al. 2004). These and many other tests are fully described in Chap. 2.

The chapter ends by offering instructional implications for health and natural sciences, and future research directions. The most frequent words of this chapter, which includes 130 references, are shown in the wordcloud of Fig. 1.1.

1.1.2 Chapter 3 – Science Education and Visuospatial Processing

The divisions of Chap. 3 are shown in Table 1.2.

In Chap. 3, Castro-Alonso and Uttal (this volume) discuss the relation between science education and visuospatial processing. This relationship stems from the fact that health and natural science communication and education rely on presenting visual and spatial representations (see Mathewson 2005).

The relation between visuospatial processing and science education has two directions (see also Castro-Alonso and Uttal 2019). One direction predicts that visuospatial processing will enhance science learning. The evidence is abundant in studies supporting this prediction, from science areas such as medicine, anatomy, surgery, biology, chemistry, and physics (e.g., Barrett and Hegarty 2016; Fiorella and Mayer 2017; Loftus et al. 2017). A common finding is that visuospatial processing is more influential in the earlier rather than the later phases of science learning

Fig. 1.1 Wordcloud for Chap. 2

Table 1.2 Structure of Chap. 3

Section
Visuospatial Processing Influencing Science Learning and Achievement
Science Education Influencing Visuospatial Processing
Visuospatial Training
Discussion

and competency (see Uttal and Cohen 2012). In other words, science knowledge eventually becomes more critical than visuospatial abilities.

The other direction of the reciprocal relationship predicts that learning science topics will aid in visuospatial processing tasks. Correlational and experimental evidence supporting this prediction has been observed in science areas as diverse as dentistry, anatomy, veterinary medicine, biology, chemistry, and physics (e.g., Gutierrez et al. 2017; Langlois et al. 2019; Lufler et al. 2012).

Besides the improvement of visuospatial abilities due to learning science concepts, another method to enhance these abilities involves *training*. Moreover, the goal of visuospatial training is that, by practicing with visuospatial tests, improvement in these tasks would ultimately lead to improvement in science tasks and general academic achievement. This *transfer* of visuospatial processing has been more difficult to obtain than its training (Stieff and Uttal 2015).

Nonetheless, there is experimental evidence encouraging to pursue transfer of visuospatial processing (see Stieff and Uttal 2015). The degree of transfer obtained can be classified as *near*, *intermediate*, and *far* (Uttal and Cohen 2012). Near transfer is, basically, training (e.g., practicing mental folding with certain shapes to improve in mental folding with similar shapes). Intermediate transfer entails a more substantial leap (e.g., practicing mental folding to improve in mental rotation). Far transfer is the most difficult to obtain (e.g., practicing mental folding to improve in molecular chemistry understanding).

The current educational efforts are oriented toward achieving far transfer. As criticized by several authors (see Langlois et al. 2019; Redick et al. 2015; Simons et al. 2016), some studies claiming to obtain far transfer have not gone that far. Sometimes their positive results can also be attributed to problems in methodology, such as lacking control groups or proper control conditions. Only by avoiding these issues, the future experiments on visuospatial training and transfer may provide more reliable results.

Chapter 3 ends by discussing implications for educators in health and natural sciences and offering possible future directions for research. The most frequent words selected for this chapter, which includes 113 references, are provided in the cloud of Fig. 1.2.

Fig. 1.2 Wordcloud for Chap. 3

Table 1.3 Structure of Chap. 4

Section
Sex Differences in Different Visuospatial Processing Abilities
Sociocultural and Biological Explanations
Visuospatial Training to Reduce Sex Differences
Discussion

1.1.3 Chapter 4 – Sex Differences in Visuospatial Processing

The four divisions of Chap. 4 are shown in Table 1.3.

In Chap. 4, Castro-Alonso and Jansen (this volume) describe the sex differences reported for various visuospatial processing tests, remarking that these differences do not always show the same degrees. For example, the most consistent finding is that men outperform women in mental rotation tests, chiefly in mental rotation tests with three-dimensional shapes (e.g., Peters et al. 1995; Reilly et al. 2016).

However, the differences in other tests tend to favor men to a smaller degree, as shown by mental rotation tests with two-dimensional shapes, mental folding tests, and other visuospatial working memory tasks (see Linn and Petersen 1985; Voyer et al. 2017).

A notable exception for the superior performance of men over women in visuospatial tests is one task in which women surpass men. This is the visual working memory task known as Object Location Memory (e.g., Eals and Silverman 1994; cf. Hammond et al. 2019).

A sociocultural cause to explain the sex differences in visuospatial processing is *visuospatial experience*. The evidence shows that men have more training than women on spatial sports and hobbies, as well as videogames and visuospatial toys (e.g., Jirout and Newcombe 2015; Voyer and Jansen 2017).

A second sociocultural explanation has been called *stereotype threat* (see Spencer et al. 2016). The stereotyped situation in which women fail in a visuospatial task, makes them attempt these tasks with concerns about confirming the negative outcome. In this scenario, the working memory resources are wasted in overthinking instead of being invested in solving the visuospatial task (Schmader and Johns 2003; Schmader et al. 2008). As a result of this divergence of cognitive resources, women fail in the visuospatial assessment.

A biological explanation for these sex differences is related to *hormones*, chiefly the male hormone of testosterone. The chapter describes studies with prenatal and adult participants. Prenatal studies with twins (e.g., Heil et al. 2011; Vuoksimaa et al. 2010) tend to support that testosterone enable female performance in visuospatial tasks. However, hormone studies, especially those with adults, have not shown consistent evidence (e.g., Courvoisier et al. 2013; Hausmann et al. 2009).

To reduce the sex differences, visuospatial training activities are recommended (see Newcombe 2016; Wai and Kell 2017). Although there is encouraging evidence showing how practicing a visuospatial test can help women (e.g., Guimarães et al. 2019; Wright et al. 2008), there are also less promising findings indicating that the initial sex gap does not always diminish with training (e.g., Peters et al. 1995).

Chapter 4 finishes by discussing implications for science educators, and future directions of inquiry for researchers. The most frequent words of this chapter, which includes 122 references, are provided in the cloud of Fig. 1.3.

Fig. 1.3 Wordcloud for Chap. 4

1.1.4 Chapter 5 – Instructional Visualizations, Cognitive Load Theory, and Visuospatial Processing

The nine sections of Chap. 5 are shown in Table 1.4.

In Chap. 5, Castro-Alonso et al. (this volume-b) discuss optimization strategies for science instructional visualizations, based on *cognitive load theory*. This theory investigates how the human cognitive architecture works for learning (see Sweller et al. 2011; see also Sweller et al. 2019). Currently, cognitive load theory has incorporated evolutionary principles that predict learning performance, for both novices and experts, in different scenarios and for diverse educational materials (see Sweller and Sweller 2006).

Chap. 5 mainly concerns university novices learning science topics through instructional visualizations. The cognitive load theory rationale most relevant to this scenario is that on the limitations of working memory to process novel information (see Cowan 2001). The visuospatial processor, being a component of working memory, is also severely limited (e.g., Luck and Vogel 1997). Under these circumstances, there are five effects or strategies that the theory has investigated with the aim to optimize visualizations (see Sweller et al. 2011; see also Mayer 2014).

Firstly, the *split-attention effect* predicts that learning from two visual elements (e.g., visualizations plus text) that are far from each other will be less effective than studying displays that are spatially contiguous (see Ayres and Sweller 2014; see also Mayer and Fiorella 2014). The strategy is particularly useful for low visuospatial students (e.g., Fenesi et al. 2016; Wiegmann et al. 1992).

Secondly, the *modality effect* predicts that studying visualizations supplemented with written texts will be less effective than learning through visualizations supplemented with auditory texts (see Low and Sweller 2014).

Thirdly, the *redundancy effect* predicts that learning from visualizations that contain more visual information than the primordial for the task will be less effective

Table 1.4 Structure of Chap. 5

Section
Science Learning Optimized through Instructional Visualizations
Cognitive Load Theory
Cognitive Load Theory Effects for Science Visualizations
Split-Attention Effect and Spatial Contiguity Principle
Modality Effect or Modality Principle
Redundancy Effect and Coherence Principle
Signaling Principle
Transient Information Effect
Discussion

than studying only the necessary information (see Kalyuga and Sweller 2014; see also Mayer and Fiorella 2014). The inclusion of extra visual information is more problematical for low rather than high visuospatial processing students (e.g., Korbach et al. 2016; Levinson et al. 2007).

Fourthly, the *signaling principle* predicts that learning from visualizations without visual signals will be less effective than studying visualizations that include cues to signal the essential learning elements and their relationships (see van Gog 2014).

Lastly, the *transient information effect* predicts that studying transient visualizations (e.g., videos and animations) will be less effective than learning through static images (see Ayres and Paas 2007). Diverse studies have supported this prediction (e.g., Castro-Alonso et al. 2014, 2018b; Höffler and Schwartz 2011; Rey et al. 2019).

The authors of Chap. 5 also discuss instructional implications and future research directions for science education. The most frequent words of this chapter, which includes 117 references, are shown in Fig. 1.4.

1.1.5 Chapter 6 – Interactive Science Multimedia and Visuospatial Processing

The structure of Chap. 6 is provided in Table 1.5.

In Chap. 6, Castro-Alonso and Fiorella (this volume) discuss the relationship between interactive multimedia and visuospatial processing. An interactive multimedia learning situation is defined as an exchange between the students' cognitive *engagement* and the multimedia's *feedback* as response (see Domagk et al. 2010).

High-level cognitive engagement is obtained from interactive and constructive actions, compared to active or passive activity (see the ICAP framework in Chi and Wylie 2014). Research on health and natural science multimedia provides several

Fig. 1.4 Wordcloud for Chap. 5

Table 1.5 Structure of Chap. 6

Section
Research Perspectives on Fostering Effective Interactivity
Simulations
Videogames
Discussion

examples of meaningful learning with these highest levels of engagement by the student (e.g., Erhel and Jamet 2006; Schwartz and Plass 2014).

Similarly, high-level feedback given by the multimedia in response to the students' actions is preferable over low-level feedback (see Hattie and Timperley 2007). Evidence of science multimedia studies support these higher levels of feedback (e.g., D. B. Clark et al. 2016; Van der Kleij et al. 2015).

However, as predicted by cognitive load theory (see Sweller et al. 2011), too much cognitive engagement (e.g., Fiorella and Mayer 2012; Stull and Mayer 2007) and visual feedback (e.g., Fiorella et al. 2012; Lin and Li 2018) can be problematic. These scenarios where too much visuospatial information is involved can overload the limited working memory capacity of the students, particularly those with less visuospatial processing capacity (see also the coherence principle in Mayer and Fiorella 2014).

Provided this overload problem is controlled, two multimedia resources that allow high-level engagement and feedback are *simulations* and *videogames*. Notable advantages of simulations over real-world laboratories are their lower costs and faster data management (Triona and Klahr 2003). The positive learning effects of simulations have been observed in studies about health sciences (e.g., Donovan et al. 2018; Kostusiak et al. 2017) and natural sciences (e.g., Blackburn et al. 2019; Parong and Mayer 2018). Similarly, various examples of science simulations show that these multimedia are more effective for students with high visuospatial processing, for example, high mental rotation ability (e.g., Huk 2006; Loftus et al. 2017).

Regarding videogames, they have also shown encouraging learning results for health and natural science topics (e.g., Cheng et al. 2014; D. B. Clark et al. 2016; Mayer 2019). Moreover, correlational and experimental evidence has supported the effectiveness of videogame playing, particularly action videogames, in training visuospatial processing (e.g., Blacker et al. 2014; Green and Bavelier 2007; Spence and Feng 2010).

Chapter 6 ends by discussing instructional implications of employing simulations and videogames for health and natural science education. The chapter also offers future directions for research in these areas. The most frequent words selected for Chap. 6, which includes 114 references, are provided in Fig. 1.5.

Fig. 1.5 Wordcloud for Chap. 6

Table 1.6 Structure of Chap. 7

Section
Executing Body Actions
Executing or Observing Body Actions
Embodied Cognition in Manipulations and Gestures
Manipulations
Gestures
Discussion

1.1.6 Chapter 7 – Embodied Cognition, Science Education, and Visuospatial Processing

The six sections of Chap. 7 are shown in Table 1.6.

In Chap. 7, Castro-Alonso et al. (this volume-c) describe relationships between *embodied cognition*, health and natural science education, and visuospatial processing. Embodied cognition can be presented as a framework in which brain, body, and environment are regarded as agents of cognitive processes (e.g., Barsalou 2008; A. Clark and Chalmers 1998).

At least six non-mutually exclusive research perspectives can explain the embodied cognition phenomena. The first three perspectives, which concern research where students execute body actions, can be called: (a) *offloaded cognition* (e.g., Ginns and Kydd 2019; Macken and Ginns 2014); (b) *generative learning* (see Fiorella and Mayer 2016b; Wittrock 1989); and (c) *physical activity* (e.g., Fenesi et al. 2018; Oppezzo and Schwartz 2014).

The other three perspectives, which concern students executing or observing body actions, are called: (a) *survival cognition* (e.g., Nairne et al. 2012; Paas and Sweller

2012; see also Sweller et al. 2019); (b) *social cognition* (e.g., Pi et al. 2019; Stull et al. 2018a); and (c) *signaling* (e.g., Fiorella and Mayer 2016a; Pi et al. 2019).

The two most investigated embodied actions for science topics and visuospatial processing are *manipulations* and *gestures*. As described in Castro-Alonso et al. (2015), both manipulations and gestures are instances of human hand actions, the difference being that manipulations depend on objects (and not as much on hands) and gestures depend on hands (and not as much on objects).

Manipulations sometimes share resources with mental manipulations, as it has been shown for mental rotation (e.g., Shepard and Metzler 1971; Wexler et al. 1998; Wohlschläger and Wohlschläger 1998) and mental folding (Shepard and Feng 1972). Due to this relationship, when using manipulatives to learn science concepts, usually having high visuospatial processing is advantageous (e.g., Barrett and Hegarty 2016; Huk 2006).

Concerning the research on gestures, the type of gesture known as pointing has provided consistent findings. When pointing is toward visual areas outside the learning elements, learning and memory is hampered (e.g., Hale et al. 1996; Lawrence et al. 2001), whereas pointing toward the learning elements can enhance learning and memory performance (e.g., Göksun et al. 2013; Li et al. 2019). There is also accumulating research showing that gestures are helpful to assist students with low visuospatial abilities.

Studies have compared the instructional effectiveness of executing versus observing gestures and manipulations. Most findings support that is more advantageous to execute than to solely observe these human hand actions (e.g., Jang et al. 2017; Kontra et al. 2015; Stull et al. 2018b).

Chapter 7 also discusses instructional implications and future directions for research. The most frequent words selected for Chap. 7, which contains 117 references, are provided in Fig. 1.6.

Fig. 1.6 Wordcloud for Chap. 7

1.1.7 Chapter 8 – VAR: A Battery of Computer-Based Instruments to Measure Visuospatial Processing

The structure of Chap. 8 is provided in Table 1.7.

In Chap. 8, Castro-Alonso et al. (this volume-a) describe *VAR* (*visuospatial adaptable resources*), a recently developed battery of seven computer-based instruments to measure different visuospatial processing abilities. The instruments have been optimized to run through the Internet in desktop computers, laptops, tablets, and mobile phones.

The battery includes an Internet administrative tool that launches, configures, and saves the data for all the instruments in VAR. This tool allows adding and deleting tests, configuring whether practices will be included or not before the actual testing, and choosing between English and Spanish languages for the instructions and texts, among other adjustments.

VAR contains two *mental rotation* instruments. The test measuring three-dimensional mental rotation is based on the pen-and-paper Mental Rotations Test (Peters et al. 1995; Vandenberg and Kuse 1978), which uses abstract shapes made with connected cubes. The test measuring two-dimensional mental rotation is based on the pen-and-paper Card Rotations Test (Ekstrom et al. 1976). The current version includes classical simple abstract figures plus 20 novel shapes (see Castro-Alonso et al. 2018a). Some variables that can be adjusted in these mental rotation instruments include: the type and number of shapes to show, their rotations, their format, and the time to answer the tests.

VAR also incorporates two *spatial working memory* instruments. One is based on the Corsi Block Tapping Test, initially developed for wooden blocks (as cited in Milner 1971), but currently produced with on-screen squares (e.g., Pilegard and Mayer 2018). The other spatial instrument is based on the n-back tests by Kirchner (1958). Three common adaptable variables in these spatial working memory tests are: the lengths of the sequence shown, the number of sequences per level, and the speed of presentation.

Our battery also includes two *visual working memory* instruments. One is adapted from the Visual Patterns Test (Della Sala et al. 1999). The other one contains two subtests, the Object Location Memory task and the Object Identity

Table 1.7 Structure of Chap. 8

Section
Administrative Tool to Manage the Instruments in VAR
Mental Rotation Instruments
Spatial Working Memory Instruments
Visual Working Memory Instruments
Dual Visuospatial Instruments of Working Memory
Discussion

Fig. 1.7 Wordcloud for Chap. 8

Memory task (e.g., Eals and Silverman 1994). All these visual tests show simultaneous stimuli that can be adjusted in variables such as: size of the visual stimuli, number of trials per level, and waiting interval time.

The last instrument of VAR can be set with different combinations of memory and processing tasks of *dual instruments of working memory*. These are based on the original test by Daneman and Carpenter (1980), and several visuospatial tests that followed (e.g., Kane et al. 2004; Shah and Miyake 1996). Variables that can be adjusted in these tasks include: the number of trials, time to present the stimuli, inter-stimuli time, starting difficulty level, and ending difficulty level.

The common data that the administrative tool records for the seven tests in VAR include, among others: the configuration of the instruments, the answers of the participants (compared with the correct answers), the total scores and correct percentages, and the time taken to solve the tests. This data can be exported to spreadsheets for later analyses.

Chapter 8 ends by discussing instructional implications and future directions for research. The most frequent words of Chap. 8, which contains 119 references, are provided in the cloud of Fig. 1.7.

1.2 Conclusion

This chapter provides an overview of the present volume, which is composed of seven additional chapters describing variables that affect the relationship between visuospatial processing and university education in health and natural sciences. As such, Chap. 2 discusses several small-scale abilities controlled by the visuospatial components of working memory. Chapter 3 describes the reciprocal relationship between visuospatial processing and science education and training. Chapter 4 presents the relationship between sex and visuospatial processing. Chapter 5 describes cognitive load theory and how it can be applied to optimize instructional visualizations, also considering the influence of visuospatial processing. Chapter 6 presents the effects of simulations, videogames, and interactive multimedia on science learning and visuospatial processing. Chapter 7 describes how manipulations and gestures affect science learning and visuospatial processing. Finally, Chap. 8 presents VAR, a novel battery of computer-adapted tests that can be tailored to measure different visuospatial processing abilities and moderating variables. In conclusion, the present book, coauthored with leading international academics, is expected to contribute to research about visuospatial processing and science education.

Acknowledgments Support from PIA–CONICYT Basal Funds for Centers of Excellence Project FB0003, and CONICYT Fondecyt 11180255, is gratefully acknowledged. I am also thankful to Enrique Castro for his assistance.

References

Atit, K., Shipley, T. F., & Tikoff, B. (2013). Twisting space: Are rigid and non-rigid mental transformations separate spatial skills? *Cognitive Processing, 14*(2), 163–173. https://doi.org/10.1007/s10339-013-0550-8.

Ayres, P., & Paas, F. (2007). Can the cognitive load approach make instructional animations more effective? *Applied Cognitive Psychology, 21*(6), 811–820. https://doi.org/10.1002/acp.1351.

Ayres, P., & Sweller, J. (2014). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 206–226). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.011.

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556–559.

Barrett, T. J., & Hegarty, M. (2016). Effects of interface and spatial ability on manipulation of virtual models in a STEM domain. *Computers in Human Behavior, 65*, 220–231. https://doi.org/10.1016/j.chb.2016.06.026.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639.

Berney, S., Bétrancourt, M., Molinari, G., & Hoyek, N. (2015). How spatial abilities and dynamic visualizations interplay when learning functional anatomy with 3D anatomical models. *Anatomical Sciences Education, 8*(5), 452–462. https://doi.org/10.1002/ase.1524.

Blackburn, R. A. R., Villa-Marcos, B., & Williams, D. P. (2019). Preparing students for practical sessions using laboratory simulation software. *Journal of Chemical Education, 96*(1), 153–158. https://doi.org/10.1021/acs.jchemed.8b00549.

Blacker, K. J., Curby, K. M., Klobusicky, E., & Chein, J. M. (2014). Effects of action video game training on visual working memory. *Journal of Experimental Psychology: Human Perception & Performance, 40*(5), 1992–2004. https://doi.org/10.1037/a0037556.

Bruyer, R., & Scailquin, J.-C. (1998). The visuospatial sketchpad for mental images: Testing the multicomponent model of working memory. *Acta Psychologica, 98*(1), 17–36. https://doi.org/10.1016/S0001-6918(97)00053-X.

Castro-Alonso, J. C., & Atit, K. (this volume). Different abilities controlled by visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 23–51). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_2.

Castro-Alonso, J. C., & Fiorella, L. (this volume). Interactive science multimedia and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 145–173). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_6.

Castro-Alonso, J. C., & Jansen, P. (this volume). Sex differences in visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 81–110). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_4.

Castro-Alonso, J. C., & Uttal, D. H. (2019). Spatial ability for university biology education. In S. Nazir, A.-M. Teperi, & A. Polak-Sopińska (Eds.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2018 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 283–291). Cham: Springer. https://doi.org/10.1007/978-3-319-93882-0_28.

Castro-Alonso, J. C., & Uttal, D. H. (this volume). Science education and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural science*s (pp. 53–79). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_3.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2014). Learning from observing hands in static and animated versions of non-manipulative tasks. *Learning and Instruction, 34*, 11–21. https://doi.org/10.1016/j.learninstruc.2014.07.005.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015). The potential of embodied cognition to improve STEAM instructional dynamic visualizations. In X. Ge, D. Ifenthaler, & J. M. Spector (Eds.), *Emerging technologies for STEAM education: Full STEAM ahead* (pp. 113–136). New York: Springer. https://doi.org/10.1007/978-3-319-02573-5_7.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018a). Computerized and adaptable tests to measure visuospatial abilities in STEM students. In T. Andre (Ed.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2017 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 337–349). Cham: Springer. https://doi.org/10.1007/978-3-319-60018-5_33.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2018b). Learning symbols from permanent and transient visual presentations: Don't overplay the hand. *Computers & Education, 116*, 1–13. https://doi.org/10.1016/j.compedu.2017.08.011.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (this volume-a). VAR: A battery of computer-based instruments to measure visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 207–229). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_8.

Castro-Alonso, J. C., Ayres, P., & Sweller, J. (this volume-b). Instructional visualizations, cognitive load theory, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 111–143). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_5.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (this volume-c). Embodied cognition, science education, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 175–205). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_7.

Cheng, M.-T., Su, T., Huang, W.-Y., & Chen, J.-H. (2014). An educational game for learning human immunology: What do students learn and how do they perceive? *British Journal of Educational Technology, 45*(5), 820–833. https://doi.org/10.1111/bjet.12098.

Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*(4), 219–243. https://doi.org/10.1080/00461520.2014.965823.

Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis, 58*(1), 7–19. https://doi.org/10.1093/analys/58.1.7.

Clark, D. B., Tanner-Smith, E. E., & Killingsworth, S. S. (2016). Digital games, design, and learning: A systematic review and meta-analysis. *Review of Educational Research, 86*(1), 79–122. https://doi.org/10.3102/0034654315582065.

Courvoisier, D. S., Renaud, O., Geiser, C., Paschke, K., Gaudy, K., & Jordan, K. (2013). Sex hormones and mental rotation: An intensive longitudinal investigation. *Hormones and Behavior, 63*(2), 345–351. https://doi.org/10.1016/j.yhbeh.2012.12.007.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*(1), 87–185. https://doi.org/10.1017/S0140525X01003922.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*(4), 450–466. https://doi.org/10.1016/S0022-5371(80)90312-6.

Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwelding visuo–spatial memory. *Neuropsychologia, 37*(10), 1189–1199. https://doi.org/10.1016/S0028-3932(98)00159-6.

Domagk, S., Schwartz, R. N., & Plass, J. L. (2010). Interactivity in multimedia learning: An integrated model. *Computers in Human Behavior, 26*(5), 1024–1033. https://doi.org/10.1016/j.chb.2010.03.003.

Donovan, L. M., Argenbright, C. A., Mullen, L. K., & Humbert, J. L. (2018). Computer-based simulation: Effective tool or hindrance for undergraduate nursing students? *Nurse Education Today, 69*, 122–127. https://doi.org/10.1016/j.nedt.2018.07.007.

Eals, M., & Silverman, I. (1994). The Hunter-Gatherer theory of spatial sex differences: Proximate factors mediating the female advantage in recall of object arrays. *Ethology and Sociobiology, 15*(2), 95–105. https://doi.org/10.1016/0162-3095(94)90020-5.

Eitel, A., Bender, L., & Renkl, A. (2019). Are seductive details seductive only when you think they are relevant? An experimental test of the moderating role of perceived relevance. *Applied Cognitive Psychology, 33*(1), 20–30. https://doi.org/10.1002/acp.3479.

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Kit of factor-referenced cognitive tests*. Princeton: Educational Testing Service.

Erhel, S., & Jamet, E. (2006). Using pop-up windows to improve multimedia learning. *Journal of Computer Assisted Learning, 22*(2), 137–147. https://doi.org/10.1111/j.1365-2729.2006.00165.x.

Fenesi, B., Kramer, E., & Kim, J. A. (2016). Split-attention and coherence principles in multimedia instruction can rescue performance for learners with lower working memory capacity. *Applied Cognitive Psychology, 30*(5), 691–699. https://doi.org/10.1002/acp.3244.

Fenesi, B., Lucibello, K., Kim, J. A., & Heisz, J. J. (2018). Sweat so you don't forget: Exercise breaks during a university lecture increase on-task attention and learning. *Journal of Applied Research in Memory and Cognition, 7*(2), 261–269. https://doi.org/10.1016/j.jarmac.2018.01.012.

Fiorella, L., & Mayer, R. E. (2012). Paper-based aids for learning with a computer-based game. *Journal of Educational Psychology, 104*(4), 1074–1082. https://doi.org/10.1037/a0028088.

Fiorella, L., & Mayer, R. E. (2016a). Effects of observing the instructor draw diagrams on learning from multimedia messages. *Journal of Educational Psychology, 108*(4), 528–546. https://doi.org/10.1037/edu0000065.

Fiorella, L., & Mayer, R. E. (2016b). Eight ways to promote generative learning. *Educational Psychology Review, 28*(4), 717–741. https://doi.org/10.1007/s10648-015-9348-9.

Fiorella, L., & Mayer, R. E. (2017). Spontaneous spatial strategy use in learning from scientific text. *Contemporary Educational Psychology, 49*, 66–79. https://doi.org/10.1016/j.cedpsych.2017.01.002.

Fiorella, L., Vogel-Walcutt, J. J., & Schatz, S. (2012). Applying the modality principle to real-time feedback and the acquisition of higher-order cognitive skills. *Educational Technology Research and Development, 60*(2), 223–238. https://doi.org/10.1007/s11423-011-9218-1.

Foster, J. L., Harrison, T. L., Hicks, K. L., Draheim, C., Redick, T. S., & Engle, R. W. (2017). Do the effects of working memory training depend on baseline ability level? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*(11), 1677–1689. https://doi.org/10.1037/xlm0000426.

Ginns, P., & Kydd, A. (2019). Learning human physiology by pointing and tracing: A cognitive load approach. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (pp. 119–129). New York: Routledge. https://doi.org/10.4324/9780429283895-10.

Göksun, T., Goldin-Meadow, S., Newcombe, N., & Shipley, T. (2013). Individual differences in mental rotation: What does gesture tell us? *Cognitive Processing, 14*(2), 153–162. https://doi.org/10.1007/s10339-013-0549-1.

Gold, A. U., Pendergast, P. M., Ormand, C. J., Budd, D. A., & Mueller, K. J. (2018). Improving spatial thinking skills among undergraduate geology students through short online training exercises. *International Journal of Science Education, 40*(18), 2205–2225. https://doi.org/10.1080/09500693.2018.1525621.

Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological Science, 18*(1), 88–94. https://doi.org/10.1111/j.1467-9280.2007.01853.x.

Guimarães, B., Firmino-Machado, J., Tsisar, S., Viana, B., Pinto-Sousa, M., Vieira-Marques, P., et al. (2019). The role of anatomy computer-assisted learning on spatial abilities of medical students. *Anatomical Sciences Education, 12*(2), 138–153. https://doi.org/10.1002/ase.1795.

Gutierrez, J. C., Chigerwe, M., Ilkiw, J. E., Youngblood, P., Holladay, S. D., & Srivastava, S. (2017). Spatial and visual reasoning: Do these abilities improve in first-year veterinary medical students exposed to an integrated curriculum? *Journal of Veterinary Medical Education, 44*(4), 669–675. https://doi.org/10.3138/jvme.0915-158R3.

Hale, S., Myerson, J., Rhee, S. H., Weiss, C. S., & Abrams, R. A. (1996). Selective interference with the maintenance of location information in working memory. *Neuropsychology, 10*(2), 228–240. https://doi.org/10.1037/0894-4105.10.2.228.

Hammond, A. G., Murphy, E. M., Silverman, B. M., Bernas, R. S., & Nardi, D. (2019). No environmental context-dependent effect, but interference, of physical activity on object location memory. *Cognitive Processing, 20*(1), 31–43. https://doi.org/10.1007/s10339-018-0875-4.

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of Educational Research, 77*(1), 81–112. https://doi.org/10.3102/003465430298487.

Hausmann, M., Schoofs, D., Rosenthal, H. E. S., & Jordan, K. (2009). Interactive effects of sex hormones and gender stereotypes on cognitive sex differences—A psychobiosocial approach. *Psychoneuroendocrinology, 34*(3), 389–401. https://doi.org/10.1016/j.psyneuen.2008.09.019.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32*(2), 175–191. https://doi.org/10.1016/j.intell.2003.12.001.

Heil, M., Kavšek, M., Rolke, B., Beste, C., & Jansen, P. (2011). Mental rotation in female fraternal twins: Evidence for intra-uterine hormone transfer? *Biological Psychology, 86*(1), 90–93. https://doi.org/10.1016/j.biopsycho.2010.11.002.

Höffler, T. N., & Schwartz, R. N. (2011). Effects of pacing and cognitive style across dynamic and non-dynamic representations. *Computers & Education, 57*(2), 1716–1726. https://doi.org/10.1016/j.compedu.2011.03.012.

Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. *Journal of Computer Assisted Learning, 22*(6), 392–404. https://doi.org/10.1111/j.1365-2729.2006.00180.x.

Jang, S., Vitale, J. M., Jyung, R. W., & Black, J. B. (2017). Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. *Computers & Education, 106*, 150–165. https://doi.org/10.1016/j.compedu.2016.12.009.

Jirout, J. J., & Newcombe, N. S. (2015). Building blocks for developing spatial skills: Evidence from a large, representative U.S. sample. *Psychological Science, 26*(3), 302–310. https://doi.org/10.1177/0956797614563338.

Kalyuga, S., & Sweller, J. (2014). The redundancy principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 247–262). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.013.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General, 133*(2), 189–217. https://doi.org/10.1037/0096-3445.133.2.189.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352–358. https://doi.org/10.1037/h0043688.

Kontra, C., Lyons, D. J., Fischer, S. M., & Beilock, S. L. (2015). Physical experience enhances science learning. *Psychological Science, 26*(6), 737–749. https://doi.org/10.1177/0956797615569355.

Korbach, A., Brünken, R., & Park, B. (2016). Learner characteristics and information processing in multimedia learning: A moderated mediation of the seductive details effect. *Learning and Individual Differences, 51*, 59–68. https://doi.org/10.1016/j.lindif.2016.08.030.

Kostusiak, M., Hart, M., Barone, D. G., Hofmann, R., Kirollos, R., Santarius, T., et al. (2017). Methodological shortcomings in the literature evaluating the role and applications of 3D training for surgical trainees. *Medical Teacher, 39*(11), 1168–1173. https://doi.org/10.1080/0142159X.2017.1362102.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition, 29*(5), 745–756. https://doi.org/10.3758/bf03200477.

Langlois, J., Bellemare, C., Toulouse, J., & Wells, G. A. (2019). Spatial abilities training in anatomy education: A systematic review. *Anatomical Sciences Education*. Advance online publication. https://doi.org/10.1002/ase.1873.

Lawrence, B. M., Myerson, J., Oonk, H. M., & Abrams, R. A. (2001). The effects of eye and limb movements on working memory. *Memory, 9*(4–6), 433–444. https://doi.org/10.1080/09658210143000047.

Lejbak, L., Crossley, M., & Vrbancic, M. (2011). A male advantage for spatial and object but not verbal working memory using the n-back task. *Brain and Cognition, 76*(1), 191–196. https://doi.org/10.1016/j.bandc.2010.12.002.

Levinson, A. J., Weaver, B., Garside, S., McGinn, H., & Norman, G. R. (2007). Virtual reality and brain anatomy: A randomised trial of e-learning instructional designs. *Medical Education, 41*(5), 495–501. https://doi.org/10.1111/j.1365-2929.2006.02694.x.

Li, W., Wang, F., Mayer, R. E., & Liu, H. (2019). Getting the point: Which kinds of gestures by pedagogical agents improve multimedia learning? *Journal of Educational Psychology*. Advance online publication. https://doi.org/10.1037/edu0000352.

Lin, L., & Li, M. (2018). Optimizing learning from animation: Examining the impact of biofeedback. *Learning and Instruction, 55*, 32–40. https://doi.org/10.1016/j.learninstruc.2018.02.005.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*(6), 1479–1498. https://doi.org/10.2307/1130467.

Loftus, J. J., Jacobsen, M., & Wilson, T. D. (2017). Learning and assessment with images: A view of cognitive load through the lens of cerebral blood flow. *British Journal of Educational Technology, 48*(4), 1030–1046. https://doi.org/10.1111/bjet.12474.

Low, R., & Sweller, J. (2014). The modality principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 227–246). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.012.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279–281. https://doi.org/10.1038/36846.

Lufler, R. S., Zumwalt, A. C., Romney, C. A., & Hoagland, T. M. (2012). Effect of visual–spatial ability on medical students' performance in a gross anatomy course. *Anatomical Sciences Education, 5*(1), 3–9. https://doi.org/10.1002/ase.264.

Macken, L., & Ginns, P. (2014). Pointing and tracing gestures may enhance anatomy and physiology learning. *Medical Teacher, 36*(7), 596–601. https://doi.org/10.3109/0142159X.2014.899684.

Mathewson, J. H. (2005). The visual core of science: Definition and applications to education. *International Journal of Science Education, 27*(5), 529–548. https://doi.org/10.1080/09500690500060417.

Mayer, R. E. (Ed.). (2014). *The Cambridge handbook of multimedia learning* (2nd ed.). New York: Cambridge University Press.

Mayer, R. E. (2019). Computer games in education. *Annual Review of Psychology, 70*, 531–549. https://doi.org/10.1146/annurev-psych-010418-102744.

Mayer, R. E., & Fiorella, L. (2014). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 279–315). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015.

McGrew, K. S. (2009). CHC theory and the human cognitive abilities project: Standing on the shoulders of the giants of psychometric intelligence research. *Intelligence, 37*(1), 1–10. https://doi.org/10.1016/j.intell.2008.08.004.

Michael, W. B., Guilford, J. P., Fruchter, B., & Zimmerman, W. S. (1957). The description of spatial-visualization abilities. *Educational and Psychological Measurement, 17*(2), 185–199. https://doi.org/10.1177/001316445701700202.

Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27*(3), 272–277.

Minear, M., Brasher, F., Guerrero, C. B., Brasher, M., Moore, A., & Sukeena, J. (2016). A simultaneous examination of two forms of working memory training: Evidence for near transfer only. *Memory & Cognition, 44*(7), 1014–1037. https://doi.org/10.3758/s13421-016-0616-9.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General, 130*(4), 621–640. https://doi.org/10.1037//0096-3445.130.4.621.

Nairne, J. S., VanArsdall, J. E., Pandeirada, J. N. S., & Blunt, J. R. (2012). Adaptive memory: Enhanced location memory after survival processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(2), 495–501. https://doi.org/10.1037/a0025728.

Ness, D., Farenga, S. J., & Garofalo, S. G. (2017). *Spatial intelligence: Why it matters from birth through the lifespan*. New York: Routledge.

Newcombe, N. S. (2016). Thinking spatially in the science classroom. *Current Opinion in Behavioral Sciences, 10*, 1–6. https://doi.org/10.1016/j.cobeha.2016.04.010.

Oliver-Hoyo, M., & Babilonia-Rosa, M. A. (2017). Promotion of spatial skills in chemistry and biochemistry education at the college level. *Journal of Chemical Education, 94*(8), 996–1006. https://doi.org/10.1021/acs.jchemed.7b00094.

Oppezzo, M., & Schwartz, D. L. (2014). Give your ideas some legs: The positive effect of walking on creative thinking. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(4), 1142–1152. https://doi.org/10.1037/a0036577.

Örün, Ö., & Akbulut, Y. (2019). Effect of multitasking, physical environment and electroencephalography use on cognitive load and retention. *Computers in Human Behavior, 92*, 216–229. https://doi.org/10.1016/j.chb.2018.11.027.

Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review, 24*(1), 27–45. https://doi.org/10.1007/s10648-011-9179-2.

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology, 110*(6), 785–797. https://doi.org/10.1037/edu0000241.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*(1), 39–58. https://doi.org/10.1006/brcg.1995.1032.

Pi, Z., Zhang, Y., Zhu, F., Xu, K., Yang, J., & Hu, W. (2019). Instructors' pointing gestures improve learning regardless of their use of directed gaze in video lectures. *Computers & Education, 128*, 345–352. https://doi.org/10.1016/j.compedu.2018.10.006.

Pilegard, C., & Mayer, R. E. (2018). Game over for Tetris as a platform for cognitive skill training. *Contemporary Educational Psychology, 54*, 29–41. https://doi.org/10.1016/j.cedpsych.2018.04.003.

Redick, T. S., Shipstead, Z., Wiemers, E. A., Melby-Lervåg, M., & Hulme, C. (2015). What's working in working memory training? An educational perspective. *Educational Psychology Review, 27*(4), 617–633. https://doi.org/10.1007/s10648-015-9314-6.

Reilly, D., Neumann, D. L., & Andrews, G. (2016). Sex and sex-role differences in specific cognitive abilities. *Intelligence, 54*, 147–158. https://doi.org/10.1016/j.intell.2015.12.004.

Rey, G. D., Beege, M., Nebel, S., Wirzberger, M., Schmitt, T. H., & Schneider, S. (2019). A meta-analysis of the segmenting effect. *Educational Psychology Review*, *31*(2), 389–419. https://doi.org/10.1007/s10648-018-9456-4.

Sanchez, C. A. (2012). Enhancing visuospatial performance through video game training to increase learning in visuospatial science domains. *Psychonomic Bulletin & Review, 19*(1), 58–65. https://doi.org/10.3758/s13423-011-0177-7.

Schmader, T., & Johns, M. (2003). Converging evidence that stereotype threat reduces working memory capacity. *Journal of Personality and Social Psychology, 85*(3), 440–452. https://doi.org/10.1037/0022-3514.85.3.440.

Schmader, T., Johns, M., & Forbes, C. (2008). An integrated process model of stereotype threat effects on performance. *Psychological Review, 115*(2), 336–356. https://doi.org/10.1037/0033-295X.115.2.336.

Schwartz, R. N., & Plass, J. L. (2014). Click versus drag: User-performed tasks and the enactment effect in an interactive multimedia environment. *Computers in Human Behavior, 33*, 242–255. https://doi.org/10.1016/j.chb.2014.01.012.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General, 125*(1), 4–27. https://doi.org/10.1037/0096-3445.125.1.4.

Shepard, R. N., & Feng, C. (1972). A chronometric study of mental paper folding. *Cognitive Psychology, 3*(2), 228–243. https://doi.org/10.1016/0010-0285(72)90005-9.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701–703. https://doi.org/10.2307/1731476.

Simons, D. J., Boot, W. R., Charness, N., Gathercole, S. E., Chabris, C. F., Hambrick, D. Z., et al. (2016). Do "brain-training" programs work? *Psychological Science in the Public Interest, 17*(3), 103–186. https://doi.org/10.1177/1529100616661983.

Smirni, P., Villardita, C., & Zappalà, G. (1983). Influence of different paths on spatial memory performance in the Block-Tapping Test. *Journal of Clinical Neuropsychology, 5*(4), 355–359. https://doi.org/10.1080/01688638308401184.

Spence, I., & Feng, J. (2010). Video games and spatial cognition. *Review of General Psychology, 14*(2), 92–104. https://doi.org/10.1037/a0019491.

Spencer, S. J., Logel, C., & Davies, P. G. (2016). Stereotype threat. *Annual Review of Psychology, 67*, 415–437. https://doi.org/10.1146/annurev-psych-073115-103235.

Stericker, A., & LeVesconte, S. (1982). Effect of brief training on sex-related differences in visual–spatial skill. *Journal of Personality and Social Psychology, 43*(5), 1018–1029. https://doi.org/10.1037/0022-3514.43.5.1018.

Stieff, M., & Uttal, D. H. (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review, 27*(4), 607–615. https://doi.org/10.1007/s10648-015-9304-8.

Stull, A. T., & Mayer, R. E. (2007). Learning by doing versus learning by viewing: Three experimental comparisons of learner-generated versus author-provided graphic organizers. *Journal of Educational Psychology, 99*(4), 808–820. https://doi.org/10.1037/0022-0663.99.4.808.

Stull, A. T., Fiorella, L., Gainer, M. J., & Mayer, R. E. (2018a). Using transparent whiteboards to boost learning from online STEM lectures. *Computers & Education, 120*, 146–159. https://doi.org/10.1016/j.compedu.2018.02.005.

Stull, A. T., Gainer, M. J., & Hegarty, M. (2018b). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction, 55*, 80–92. https://doi.org/10.1016/j.learninstruc.2017.09.008.

Sweller, J., & Sweller, S. (2006). Natural information processing systems. *Evolutionary Psychology, 4*, 434–458.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York: Springer.

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive architecture and instructional design: 20 years later. *Educational Psychology Review, 31*(2), 261–292. https://doi.org/10.1007/s10648-019-09465-5.

Triona, L. M., & Klahr, D. (2003). Point and click or grab and heft: Comparing the influence of physical and virtual instructional materials on elementary school students' ability to design experiments. *Cognition and Instruction, 21*(2), 149–173.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how? In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 57, pp. 147–181). San Diego: Academic Press. https://doi.org/10.1016/B978-0-12-394293-7.00004-2.

Van der Kleij, F. M., Feskens, R. C. W., & Eggen, T. J. H. M. (2015). Effects of feedback in a computer-based learning environment on students' learning outcomes: A meta-analysis. *Review of Educational Research, 85*(4), 475–511. https://doi.org/10.3102/0034654314564881.

van Gog, T. (2014). The signaling (or cueing) principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 263–278). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.014.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*(2), 599–604. https://doi.org/10.2466/pms.1978.47.2.599.

Voyer, D., & Jansen, P. (2017). Motor expertise and performance in spatial tasks: A meta-analysis. *Human Movement Science, 54*, 110–124. https://doi.org/10.1016/j.humov.2017.04.004.

Voyer, D., Voyer, S. D., & Saint-Aubin, J. (2017). Sex differences in visual-spatial working memory: A meta-analysis. *Psychonomic Bulletin & Review, 24*(2), 307–334. https://doi.org/10.3758/s13423-016-1085-7.

Vuoksimaa, E., Kaprio, J., Kremen, W. S., Hokkanen, L., Viken, R. J., Tuulio-Henriksson, A., et al. (2010). Having a male co-twin masculinizes mental rotation performance in females. *Psychological Science, 21*(8), 1069–1071. https://doi.org/10.1177/0956797610376075.

Wai, J., & Kell, H. J. (2017). What innovations have we already lost?: The importance of identifying and developing spatial talent. In M. S. Khine (Ed.), *Visual-spatial ability in STEM education: Transforming research into practice* (pp. 109–124). Cham: Springer. https://doi.org/10.1007/978-3-319-44385-0_6.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817–835. https://doi.org/10.1037/a0016127.

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition, 68*(1), 77–94. https://doi.org/10.1016/S0010-0277(98)00032-8.

Wiegmann, D. A., Dansereau, D. F., McCagg, E. C., Rewey, K. L., & Pitre, U. (1992). Effects of knowledge map characteristics on information processing. *Contemporary Educational Psychology, 17*(2), 136–155. https://doi.org/10.1016/0361-476X(92)90055-4.

Wilson, L., Scott, J. H., & Power, K. G. (1987). Developmental differences in the span of visual memory for pattern. *British Journal of Developmental Psychology, 5*(3), 249–255. https://doi.org/10.1111/j.2044-835X.1987.tb01060.x.

Wittrock, M. C. (1989). Generative processes of comprehension. *Educational Psychologist, 24*(4), 345–376. https://doi.org/10.1207/s15326985ep2404_2.

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of Experimental Psychology: Human Perception and Performance, 24*(2), 397–412. https://doi.org/10.1037/0096-1523.24.2.397.

Wong, M., Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018). Investigating gender and spatial measurements in instructional animation research. *Computers in Human Behavior, 89*, 446–456. https://doi.org/10.1016/j.chb.2018.02.017.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review, 15*(4), 763–771. https://doi.org/10.3758/PBR.15.4.763.

Chapter 2
Different Abilities Controlled by Visuospatial Processing

Juan C. Castro-Alonso and Kinnari Atit

Visuospatial processing in working memory allows the control of diverse cognitive abilities. In fact, these visuospatial abilities are so varied that their categorization has proven difficult. For example, in a review published four decades ago, McGee (1979) noted that the studies on *spatial abilities*, which had been accumulating from the 1930s, could not reach a standard classification. Nowadays, although there are attempts to categorize spatial and visuospatial abilities (e.g., Buckley et al. 2018; Uttal et al. 2013), the puzzle is still not fully solved, nor do we try to solve it here.

In contrast to a classification goal, the aim of this chapter is to show the diversity of cognitive abilities that are controlled by the visuospatial processor of working memory, and to describe some of the common tests to measure them in adult university students. As the same processor controls these different abilities, they share many features and tend to be correlated. However, they also have crucial differences. Acknowledging these differences could help future research on the most suitable abilities for learning about health and natural sciences in different educational scenarios. To attain this goal, in the next section we describe working memory and their allocated components to deal with visuospatial ability tasks.

2.1 Visuospatial Processing by Working Memory

Recently, Könen et al. (2016) defined *working memory* as a system with limited capacity, which allows the brief storage and processing of information for higher-level cognition. The latter includes cognitive activities such as science learning

---

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

K. Atit
Graduate School of Education, University of California, Riverside, CA, USA

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_2

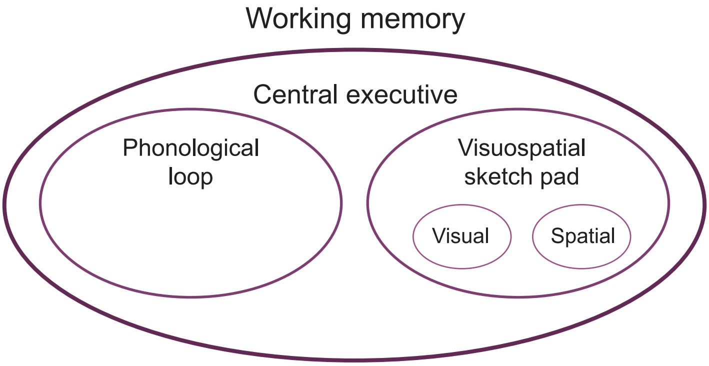


Fig. 2.1 The different components of Baddeley's working memory model

and visuospatial processing. The multicomponent model of Baddeley and Hitch (1974; see Baddeley 1992) describes working memory in more detail. In this model, there is a central attentional controller, the *central executive*, which commands two slave storage systems.

One of these slave systems is the *phonological loop*, which processes verbal and auditory information. The other slave system is the *visuospatial sketch pad*, which processes visual and spatial information (see Fig. 2.1). The model predicts that the phonological loop and the visuospatial sketch pad process information separately (e.g., Bruyer and Scailquin 1998; Shah and Miyake 1996). Furthermore, there is also a degree of independence inside the visuospatial sketch pad, as visual and spatial information tend to be processed separately within the system (e.g., Darling et al. 2006; Della Sala et al. 1999; Kozhevnikov et al. 2010).

As visuospatial processing is the focus of this chapter (and this book), the emphasis is outside the boundaries of the phonological loop and the processing of verbal and auditory information. More specifically, the focus is placed: (a) primarily, on the visuospatial sketch pad, the system for storage of visual and spatial information; and (b) secondarily, on the central executive, the system for processing and manipulating this visuospatial information.

As visuospatial processing entails managing visual and spatial information in working memory, it comprises a myriad of different cognitive abilities. Building from the definitions of *visual processing* (McGrew 2009) and *spatial thinking* (Ness et al. 2017), we define visuospatial processing as the ability to generate, recognize, transform, store, and retrieve visuospatial information, in both static and dynamic displays. In more detail, visuospatial processing entails the following tasks (see also Ness et al. 2017):

- visualizing and recognizing relationships;
- observing and predicting the behavior of objects, in both static and dynamic systems;

- transforming visuospatial information from two to three dimensions, and vice versa;
- conceptualizing space; and
- using geometric models and other visuospatial instruments.

In short, visuospatial processing in working memory allows one to carry out many visual and spatial tasks, such as the object-based versus the environmental tasks described next.

2.2 Two Scales of Visuospatial Processing

In his description of the different kinds of intellectual abilities, Thurstone (1950) defined seven visual thinking abilities, three of which involved spatial thinking. Two of the spatial factors were described as abilities to solve spatial problems of objects, independent of the orientation of the solver. The third factor was defined as an ability to solve spatial problems in which the orientation of the solver's body was pertinent. As such, the third factor was differentiated from the other two.

More recent literature follows this separation. On the one hand, there are the abilities that have been called *object manipulation* (e.g., Kozhevnikov and Hegarty 2001), *within-object manipulation* (e.g., Sanchez and Wiley 2017), *object-based* (e.g., Hegarty and Waller 2004), *allocentric* (e.g., Kozhevnikov et al. 2013), or *small-scale* (Hegarty et al. 2006) spatial abilities; on the other hand, there are those termed as *environmental*, *large-scale* (e.g., Hegarty et al. 2006), or *egocentric* (e.g., Hegarty and Waller 2004) spatial abilities.

Evidence suggests that these two groups of abilities (i.e., small-scale spatial abilities versus large-scale spatial abilities) are separable, but still somehow interrelated. For example, in a study with 353 psychology university students (56% females), Pearson and Ialongo (1986) measured four standard small-scale spatial abilities and two new large-scale environmental skills. Results showed that measures of small-scale spatial ability were more correlated with each other than with the tests of large-scale spatial ability. A factor analysis for the six tasks supported this observation, as a two-factor solution emerged, revealing one factor for the four small-scale tasks and another factor for the environmental tests. Even though the small-scale tasks were a distinct factor from the large-scale tasks, the two factors were still significantly correlated ($r = .37$, $p < .001$), showing a shared variance of more than 13%.

Additionally, in two experiments with a total of 203 participants (55% females), Allen et al. (1996) reported the relation between three small-scale abilities, assessed using standardized measures, and the environmental ability of route learning. Kozhevnikov and Hegarty (2001) developed two original tests to measure environmental spatial ability, called the *Object Perspective Test* and the *Map Perspective Test*, and contrasted these tests with known instruments of small-scale object spatial ability. Employing the data of undergraduate students who had completed the two types of spatial ability tests, the authors conducted confirmatory factor analyses. They observed that a two-factor model was a better fit for the data than a one-factor solution.

In a follow-up study with undergraduate participants, Hegarty and Waller (2004) measured large-scale spatial ability with a more difficult Object Perspective Test and a novel *Pictures Test.* For small-scale spatial ability, they used several tests of mental rotation (see Sect. 2.3.1). They replicated the main finding that a two-factor model, which separated object and environmental spatial abilities, was better than a solution with one global spatial ability factor. However, both studies showed substantial correlations between the small and large spatial factors, sharing from 50% to 65% of the variance.

In another study with 221 adults (62% females), Hegarty et al. (2006) assessed the relationship between small-scale tasks, such as mental rotation and field independence tests (see Sect. 2.3.3), and large-scale navigational tasks. They observed that small-scale spatial ability was not strongly connected to large-scale ability. The results supported a *partial dissociation model* between the two scales, as they relied on common processes but each one also depended on unique processes that they did not share.

Lastly, a more comprehensive finding was provided by the meta-analysis of 91 effect sizes (from 15 studies) and more than 13,000 participants by Wang et al. (2014). The study revealed a significant correlation (r = .27) between small and environmental spatial abilities, sharing approximately 7% of the common variance. According to Cohen (1988), this correlation corresponds to an overall small to medium effect.

In conclusion, these studies show that small-scale and large-scale spatial abilities are separate abilities, although they share elements in common. Here we will focus and describe in detail small-scale visuospatial abilities as they play a pivotal educational role in health and natural sciences (see Castro-Alonso and Uttal this volume, Chap. 3; see also Castro-Alonso and Uttal 2019).

2.3 Small-Scale Visuospatial Processing Abilities

As described by Hegarty et al. (2006), two different research traditions typically measure small-scale visuospatial abilities. On the one hand, there are the object or small-scale *spatial ability* tests (e.g., Michael et al. 1957). On the other hand, there are the visual and spatial *working memory* tasks (e.g., Milner 1971). Since both the spatial ability and the working memory research lines measure cognitive abilities in representing, memorizing, and transforming information that is visual and spatial, performance in these different visuospatial processing tasks is generally related (see Sect. 2.4).

In this chapter, both research streams are combined and jointly termed *small-scale visuospatial processing abilities*. From both research categories, the most common visuospatial tasks and standard tests are described below. A summary is presented in

Table 2.1 Small-scale visuospatial processing abilities and common tests to their measurement

Research tradition	Visuospatial ability	Common tests
Spatial ability	3D mental rotation	Mental Rotations Test, Purdue Visualization of Rotations, Cube Comparisons Test, Tube Figures Test
	2D mental rotation	Card Rotations Test, Flags Test, Mirror Pictures
	Mental folding	Paper Folding Test, Surface Development Test, Form Board Test, Spatial Visualization
	Field independence	Hidden Figures Test, Hidden Patterns Test, Group Embedded Figures Test, Find A Shape Puzzle
Working memory	Spatial working memory	Corsi Block Tapping Test, Spatial N-Back Task
	Visual working memory (Square patterns)	Visual Patterns Test, Visual Span Test, Grid Locations
	Visual working memory (Identity or position of objects)	Object Identity Memory, Object Location Memory
	Dual visuospatial tasks of working memory	Counting Span, Rotation Span, Symmetry Span, Dot Matrix, Alignment Span

Table 2.1. Additional descriptions of several of these tasks can be found in Castro-Alonso et al. (this volume-a, Chap. 8) and in Castro-Alonso et al. (2018a).

2.3.1 Mental Rotation

Mental rotation (also termed *spatial relations* or *speeded rotation*) is one of the two small-scale space factors defined by Thurstone (1950). Mental rotation involves perceiving a whole figure and visualizing its rotation in the mind (e.g., Ekstrom et al. 1976). Shepard and Metzler (1971) reported what has been a landmark of mental rotation: In a study with eight adults comparing pairs of abstract shapes in different rotations, the authors observed that the greater the angular difference between both shapes, the longer it took to do the comparison task. In other words, it appears that mental rotation is the mental equivalent of a physical "real world" rotation (see also Castro-Alonso et al. this volume-c, Chap. 7).

Several studies have shown that mental rotation needs the visuospatial sketch pad. What is less conclusive is whether mental rotation is more reliant on visual or spatial resources. For example, in two experiments totaling 30 adult participants (80% females), Hyun and Luck (2007) observed that mental rotation of letters was disrupted by a visual task but not by a spatial task. In contrast, in an experiment with 16 undergraduates (50% females), Bruyer and Scailquin (1998) employed dual tasking to observe that mental rotation was disrupted by both spatial and central executive secondary tasks. Hence, the evidence shows that mental rotation is processed by the visuospatial sketch pad and the central executive, but whether it is more dependent on visual or spatial processing is still unclear.

As shown in Table 2.1, mental rotation can be further divided into three-dimensional (3D) and two-dimensional (2D) tasks. For the former, 3D objects are rotated, thus employing three axes of rotation. In the latter, 2D shapes are rotated, which needs only two axes of rotation. For both 3D and 2D versions, the instruments that measure mental rotation typically involve comparing a target shape against "same" (rotated) or "different" (mirrored and rotated) figures. A key difference between 3D and 2D mental rotation is that the instruments with 3D shapes tend to show larger sex differences favoring males over females (see Castro-Alonso and Jansen this volume, Chap. 4). Possibly due to this interesting difference, the research on mental rotation, including its relationship to science education, has tended to employ more the 3D than the 2D instruments.

Common or standard tests that measure mental rotation with shapes in 3D are: (a) the *Mental Rotations Test*, (b) the *Purdue Visualization of Rotations*, (c) the *Cube Comparisons Test*, and (d) the *Tube Figures Test*. The Mental Rotations Test was originally developed by Vandenberg and Kuse (1978) from the abstract shapes used by Shepard and Metzler (1971) in their seminal study. The modern version by Peters et al. (1995) is the most popular pen-and-paper version and is still commonly used today. In every item of the Mental Rotations Test, participants are given one abstract 3D shape made of ten connected unit cubes (resembling the shapes in the videogame Tetris™), and four comparable 3D images at the side. The task is to find the two figures that are rotated versions of the given shape. The other two shapes in the four shapes provided are rotated and mirrored and must be left blank in the paper test (see Fig. 2.2a).

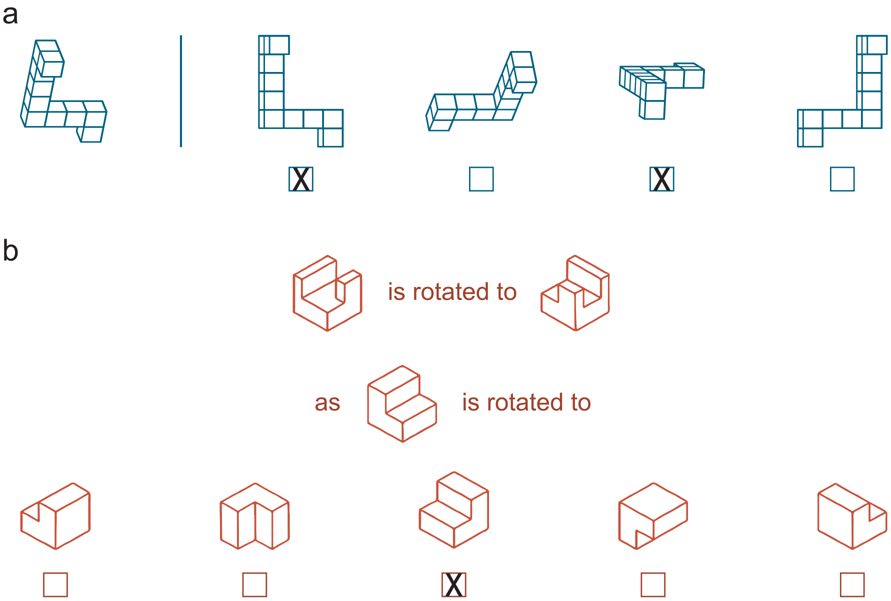


Fig. 2.2 Adapted items from (**a**) the Mental Rotations Test, and (**b**) the Purdue Visualization of Rotations. The correct answer in each case is given. Note that these are not actual items, but adaptations

The Mental Rotations Test is probably the most common test of mental rotation and possibly of spatial ability in general. Arguably, it has been used in studies examining spatial cognition in all science disciplines, including: (a) human anatomy (Berney et al. 2015; Garg et al. 2001; Jang et al. 2017; Stull et al. 2009); (b) human dentistry (Hegarty et al. 2009; Kozhevnikov et al. 2013); (c) human surgery (Wanzel et al. 2002); (d) zoology (Imhof et al. 2013); (e) general chemistry (Hinze et al. 2013); (f) organic chemistry (Stull et al. 2018); (g) physics (Kozhevnikov and Thornton 2006; Peters et al. 1995); and (h) geology (Atit et al. 2013; I. Resnick and Shipley 2013).

In the Purdue Visualization of Rotations test (e.g., Pribyl and Bodner 1987; see also Bodner and Guay 1997), participants are given two identical 3D shapes, in which one has been rotated in relation to the other. The task is to determine how the shape was rotated, and then apply the same rotation to a new shape from five possible alternatives (see Fig. 2.2b). The Purdue Visualization of Rotations test has also been utilized in studies examining spatial cognition in different science disciplines, such as: animal anatomy (Provo et al. 2002), general chemistry (Hinze et al. 2013), organic chemistry (Aldahmash and Abraham 2009), and geology (Gold et al. 2018).

The Cube Comparisons Test was produced by Ekstrom et al. (1976). The test involves comparing two cubes with different letters on their faces, and answering if both cubes are rotated depictions of each other or completely different. The Cube Comparisons Test has been used in studies about science topics such as: microscopic and macroscopic biology (Fiorella and Mayer 2017; Lord 1990), physics (Lee and Shin 2011), and geology (Piburn et al. 2005).

The last common 3D mental rotation test is the Tube Figures Test, in which the participant must compare two side-by-side photographs of a flexible tube in different positions, and determine the side from which the right image is presented in comparison to the left depiction. The Tube Figures Test has been investigated in relation to achievement in diverse biology topics (e.g., Huk and Steinke 2007; Huk et al. 2010).

In contrast to 3D instruments, regular tests that measure mental rotation in 2D are: (a) the *Card Rotations Test*, (b) the *Flags Test*, and (c) *Mirror Pictures*. The Card Rotations Test was developed by Ekstrom et al. (1976). In every item of the test, participants are given one abstract shape, and eight different depictions of it on the side. They must determine which of these depictions are the same shape, only rotated, and which are both rotated and mirrored. Examples of science studies using the Card Rotations Test include contents as diverse as: medicine (Kalet et al. 2012), biology (Seufert et al. 2009), and geology (Sanchez 2012). Among non-science examples, there is research with object manipulations (Wong et al. 2018) and abstract tasks (Castro-Alonso et al. 2014, 2018b).

The Flags Test (e.g., Hegarty and Waller 2004; Miyake et al. 2001a) involves judging which six rotated flags can be matched to the test flag. Concerning the Mirror Pictures (e.g., Hausmann et al. 2009), participants are shown four simple line illustrations that are only rotated, plus a fifth drawing that is also mirrored, and they must find each of these reflected images. In addition to these common tests, there are several mental rotation instruments that have been used with customized 2D shapes, such as: abstract geometric shapes (Heil and Jansen-Osmann 2008), molecular diagrams (Stieff 2007), alphanumeric characters (Kail 1986), and grid patterns (Bethell-Fox and Shepard 1988).

2.3.2 Mental Folding

Mental folding (also termed *spatial visualization*) is the second of the two small-scale factors defined by Thurstone (1950). This category of spatial ability comprises mental rotation and also involves processes such as mental restructuring and serial operations (e.g., Ekstrom et al. 1976). Because mental folding relies partially on mental rotation, both spatial abilities share similarities. For example, in the nomenclature about spatial abilities by Uttal et al. (2013), both were considered *intrinsic* and *dynamic* abilities. Both mental folding and mental rotation are categorized as intrinsic spatial abilities because they both involve the mental transformation of the properties of a single object by itself, not considering other surrounding objects. They are also regarded as dynamic spatial abilities because they both involve imagining the object in motion, such as imagining rotations or folds.

Possibly due to the similarity between these spatial abilities, mental folding scores are usually correlated with mental rotation scores (see Sect. 2.4). Also, as observed by Shepard and Feng (1972), tasks involving more steps of mental folding (or unfolding) will take longer than tasks that involve fewer folds. Hence, as in mental rotation, mental folding is a mental simulation of the task with real physical manipulations (see also Castro-Alonso et al. this volume-c, Chap. 7).

Nevertheless, mental folding and mental rotation also have differences. For example, Thurstone (1950) described mental rotation as transformations on rigid objects, whereas mental folding was defined as transformations where objects could change their configurations. Similarly, Thomas F. Shipley and colleagues have categorized mental rotation as a *rigid mental transformation*, because the distances between the points of the processed visualizations are preserved. In contrast, they called mental folding a *non-rigid mental transformation*, as the distances between the points of the processed visualizations are not maintained (Atit et al. 2013; I. Resnick and Shipley 2013).

There are also some indications that these two abilities differ in recruiting working memory resources. For example, in a study with 167 undergraduates, Miyake et al. (2001a) reported that more investment of the central executive was needed for mental folding than for mental rotation. Also, one of the most consistent differences between both spatial abilities is that the effect of sex or gender, favoring males, is larger for mental rotation (chiefly in 3D mental rotation) than for mental folding (see Castro-Alonso and Jansen this volume, Chap. 4).

Common tests that measure mental folding are: (a) the *Paper Folding Test*, (b) the *Surface Development Test*, (c) the *Form Board Test*, and (d) *Spatial Visualization*. The Paper Folding Test (see also *Punched Holes* in Michael et al. 1957) was developed by Ekstrom et al. (1976). Every item of the Paper Folding Test shows a sequence of folds made to a sheet of paper, and then how the folded paper was

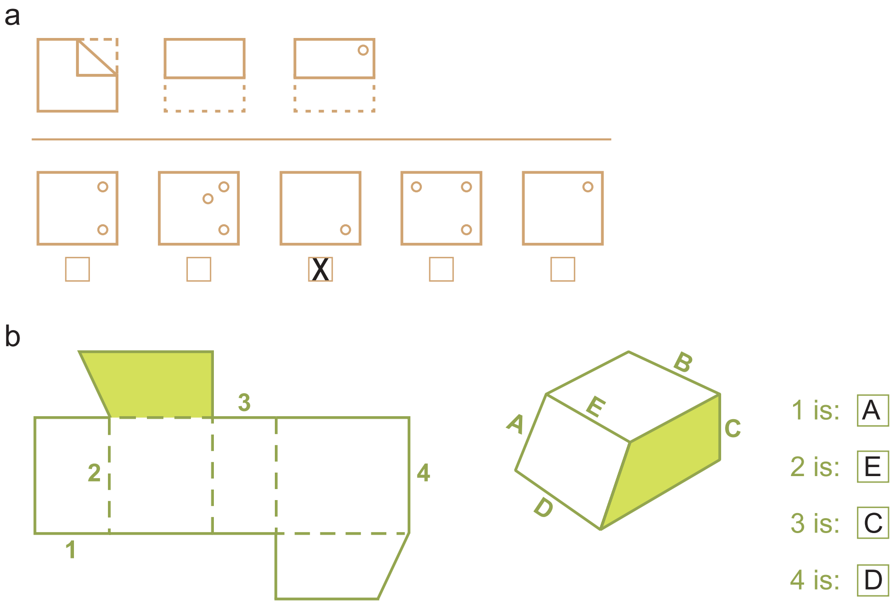


Fig. 2.3 Adapted items from (**a**) the Paper Folding Test, and (**b**) the Surface Development Test. The correct answer in each case is given. Note that these are not actual items, but adaptations

punctured. The participants must determine what the paper would look like unfolded after the holes were punched (see Fig. 2.3a). Results of this test have been related to performance in science tasks involving: (a) surgery (Keehner et al. 2004); (b) biology (Fiorella and Mayer 2017; Lord 1990; Seufert et al. 2009); (c) physics (Kozhevnikov et al. 2007; Kozhevnikov and Thornton 2006; Lee and Shin 2011); (d) astronomy (Kühl et al. 2018); and (e) geoscience (Atit et al. 2013; Eitel et al. 2019; Hambrick et al. 2012; Wiley 2019). It has also been used in relation to abstract tasks of memorizing the positions of symbols (Castro-Alonso et al. 2014).

The Surface Development Test (see also *Pattern Comprehension* in Michael et al. 1957) was also included in the battery of Ekstrom et al. (1976). The participants must imagine how a 2D depiction would fold into a given 3D object (see Fig. 2.3b). This test has been used in diverse scenarios, including learning topics of health and natural sciences (Piburn et al. 2005; Ruisoto et al. 2014), attempting visuospatial processing tasks (Allen et al. 1996; Hunt et al. 1988), and training with spatial videogames (Terlecki et al. 2008).

The task in the Form Board Test (see Ekstrom et al. 1976) is to determine which smaller shapes from five alternatives are needed to make a larger shape. This test has been linked to performance in tasks such as: physics problems of motion (Kozhevnikov et al. 2007), geological bedrock mapping (Hambrick et al. 2012), and Tetris videogame training (Pilegard and Mayer 2018).

Lastly, the test of Spatial Visualization (e.g., Michael et al. 1957) involves imagining how folded and cut pieces of paper would look when unfolded. There are also less common tests to measure mental folding, such as: the *Mental Paper-Folding Task* (e.g., Shepard and Feng 1972; Wright et al. 2008), and the *Paper Folding and Cutting* subtest (e.g., Jaušovec and Jaušovec 2012).

2.3.3 Field Independence

The third construct from the spatial ability research tradition is field independence. Arguably, the seminal work in this ability was conducted by Witkin and colleagues in the late 1940s. For example, Witkin (1949) described tests in real environments and a related pen-and-paper instrument that measured the capacity to perceive an object independently of its context. When defining the seven primary visual thinking abilities, Thurstone (1950) described two closure factors, with the second one being directly related to field independence.

Similar to mental rotation and mental folding, field independence may also rely both on the visuospatial sketch pad and the central executive of working memory. Support for this notion is given by Miyake et al. (2001b) in a study with 75 undergraduate students attempting a field independence task (the Hidden Figures Test) in different dual task conditions. It was observed that the performance on the Hidden Figures Test was only disrupted when the secondary tasks involved the visuospatial or the executive components of working memory.

Standard or common tests that measure field independence are: (a) the *Hidden Figures Test*, (b) the *Hidden Patterns Test*, (c) the *Group Embedded Figures Test*, and (d) the *Find A Shape Puzzle*. The Hidden Figures Test, developed by Ekstrom et al. (1976), asks to decide which of five simple geometrical shapes is taken from a complex image (see Fig. 2.4). This test has been used, for examples, in: investigating correlations with surgical skills (Gibbons et al. 1986), assessing undergraduate biology students (Lord 1990), measuring spatial training in geology undergraduates (Gold et al. 2018), comparing performance of professors of different disciplines (I. Resnick and Shipley 2013), and measuring adults in small-scale and large-scale spatial abilities (Allen et al. 1996).

In the Hidden Patterns Test, also included in the battery by Ekstrom et al. (1976), each item shows a simple pattern and participants must determine whether ten com-

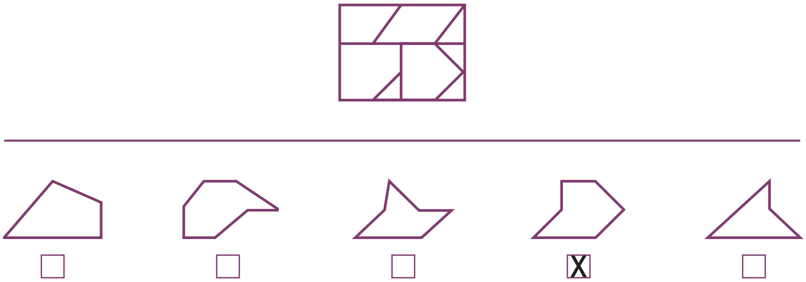


Fig. 2.4 Adapted item from the Hidden Figures Test. The correct answer is shown

plex figures hide this pattern or not. This test was employed in the seminal report for the Mental Rotations Test (Vandenberg and Kuse 1978), where the mental rotation instrument showed significant correlations with the Hidden Patterns Test. Another study that used this test was S. M. Resnick et al. (1986), who investigated hormone influence on visuospatial processing.

Similarly, the Group Embedded Figures Test entails finding a simple figure from more complex shapes. Studies using this test have reported: relationships between field independence and both small and larger scale visuospatial abilities (Hegarty et al. 2006; Stericker and LeVesconte 1982); and correlations between this test and scores in human anatomy tasks (Berney et al. 2015) or in concept maps about the autonomic nervous system (Wiegmann et al. 1992).

Regarding the Find A Shape Puzzle, an instrument developed initially by Linn and Kyllonen (1981), the participants must find a simple shape inside five complex images. Examples of uses of the Find A Shape Puzzle include: examining the relations between field independence and chemistry results in university students (Pribyl and Bodner 1987), and investigating the effects of visuospatial processing on learning organic chemistry from static and animated visualizations (Aldahmash and Abraham 2009).

2.3.4 Spatial Working Memory

As described in Sect. 2.1, there is a degree of independent working memory processing between spatial and visual information. Following this separation, there are standard tests designed to investigate these different cognitive resources. Usually, tests that measure spatial working memory involve presenting visual elements sequentially (e.g., the Corsi Block Tapping Test, see Milner 1971); in contrast, tests that measure visual working memory present the elements simultaneously (e.g., Ashkenazi and Shapira 2017). In other words, and as cautioned by Darling et al. (2006), sometimes is not simple to determine if a test is measuring either the processing of spatial or of sequential information, as is not easy to conclude if another instrument is measuring either visual or simultaneous stimuli.

As such, the following tests, measuring mostly the spatial component of visuospatial working memory, can also be categorized as measures of sequential (and not simultaneous) visual stimuli. Common tests measuring this ability from the working memory tradition (see Table 2.1) are: (a) the *Corsi Block Tapping Test*, and (b) the *Spatial N-Back Task*.

The Corsi Block Tapping Test was developed originally by Corsi (as cited in Milner 1971), in a physical version with nine wooden blocks distributed on a board. In this traditional wooden version of the Corsi test, the participants must tap the same sequence of blocks as shown by the experimenter. Usually, the sequences start shorter, such as a 3-Block series, and increase in length, for example finishing in a 9-Block sequence (e.g., Smirni et al. 1983), thus increasing in difficulty. In contrast to the use of 3D volumetric blocks, nowadays the Corsi test is used in virtual versions with 2D

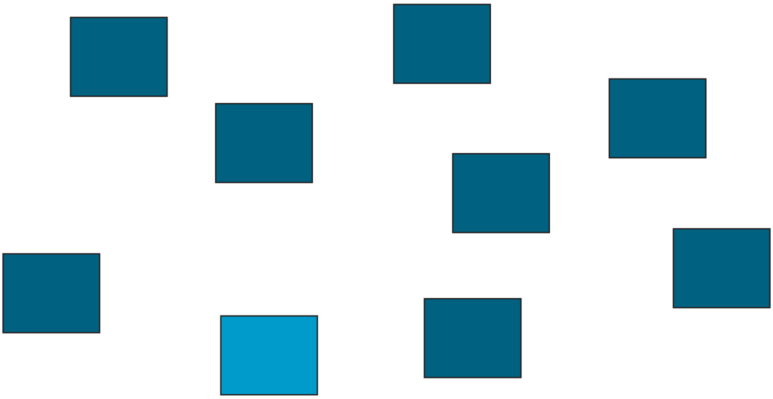


Fig. 2.5 A square highlighted in a 2D virtual version of the Corsi Block Tapping Test

squares on the screen (e.g., Ashkenazi and Shapira 2017; Cornoldi and Mammarella 2008; Pilegard and Mayer 2018; Wong et al. 2018). For example, Fig. 2.5 shows an adaptation of the virtual version that was used by Castro-Alonso et al. (2018b).

In both the wooden or computer versions of the test, the participant can be tasked with reproducing the sequence in either the forward or backward direction. When providing a backward response, the sequence must be copied in the reverse order. As this backward direction is more challenging, it may recruit more central executive resources (e.g., Miyake et al. 2001a) and be more strongly related to other visuospatial processing skills (e.g., Cornoldi and Mammarella 2008), compared to the traditional or forward direction.

When solving the Corsi Block Tapping Test, students employ the visuospatial component of working memory, but they also get assistance from the central executive. For example, Vecchi and Richardson (2001) assessed the performance of 20 adult participants (50% females) in the test, while performing either visuospatial, verbal, or central executive interfering tasks. The study revealed that simultaneous visuospatial or central executive tasks hindered performance on the Corsi test. Comparable results were observed by Vandierendonck et al. (2004) in three experiments with a total of 86 psychology undergraduates, where visuospatial interference negatively affected test performance on all levels and central executive interference diminished performance only on the difficult trials. Analogously, after three experiments with a sum of 56 university students (57% females), Rudkin et al. (2007) concluded that sequential tests such as the Corsi Block Tapping Test invested more central executive resources than simultaneous tests (e.g., the Visual Patterns Test, see Sect. 2.3.5). In conclusion, the Corsi Block Tapping Test is a visuospatial instrument that measures: (a) mostly spatial working memory; and (b) also central executive resources, particularly in its backward direction.

Other instruments of spatial working memory follow the n-back paradigm, introduced by Kirchner (1958) using sequences of flashing lights. Several visuospatial versions of the paradigm have been developed, and we categorized them as different instances of the Spatial N-Back Task. In every trial of these tasks, participants must determine if a specific visuospatial stimulus has already been presented. For example, for a Spatial 2-Back Task, participants are presented with Stimulus X, blank interval, Stimulus Y, blank interval, and Test Stimulus. Then, participants must answer if the Test Stimulus is the same or different to the one presented two stimuli back (i.e., Stimulus X). There are several examples of these 2-back tests (e.g., Hautzel et al. 2002; Lejbak et al. 2011; see also Castro-Alonso et al. this volume-a, Chap. 8).

To develop more difficult n-back tasks, the length can be increased to 3-back (e.g., McEvoy et al. 1998; Schmiedek et al. 2009) and reach extremes such as 8-back (Schwarb et al. 2016). Another way to increase difficulty is by increasing the complexity of the stimuli. Typically, the Spatial N-Back Task uses patterns of squares, in which one of the squares in the pattern is randomly marked. Thus, to increase the difficulty of the patterns, the versions that use a 3 × 3 diagram of nine squares (e.g., Minear et al. 2016; Stephenson and Halpern 2013) can be made more difficult by increasing the size of the diagram. For example, a more difficult task may use patterns of 4 × 3 (McEvoy et al. 1998), 4 × 4 (Schmiedek et al. 2009), or 5 × 5 squares (Schwarb et al. 2016). A third form to increase difficulty is to present the stimuli more rapidly (e.g., Schmiedek et al. 2009).

2.3.5 Visual Working Memory

In this second construct from the working memory research, these instruments, which measure mostly the visual component of visuospatial working memory, can also be categorized as measures of simultaneous (and not sequential) visual stimuli (see Darling et al. 2006). We consider two types of instruments, as shown in Table 2.1: (a) square patterns, and (b) identity or position of objects. In the first category of tests that imply memorizing positions in square patterns, we include three instruments: (a) the *Visual Patterns Test*, (b) the *Visual Span Test*, and (c) *Grid Locations*.

The Visual Patterns Test is arguably the most popular in this group. It was developed by Della Sala et al. (1999), based on the previous work by Phillips and Baddeley (1971) who devised grids of 5 × 5 squares, randomly half blank and half filled. This first attempt incorporated later the option to increase the difficulty by adding squares to the grids (e.g., Wilson et al. 1987). The Visual Patterns Test (Della Sala et al. 1999) starts with easier grids of four squares (2 × 2 patterns), and increases difficulty by adding two squares per level, until the most difficult trials of 30 squares (6 × 5 patterns; see Fig. 2.6). In every trial, participants must memorize which are the filled squares, so then from memory they fill the squares in an empty test grid.

In an experiment with 16 undergraduates (44% females), Della Sala et al. (1999) employed interfering visual and spatial tasks to test how these would hinder performance on a visual test (the Visual Patterns Test) versus a spatial test (the Corsi Block Tapping Test). As the results showed selective interferences, it was concluded that the Visual Patterns Test was an instrument tailored to measure the visual component of visuospatial working memory, whereas the Corsi Block Tapping Test was more

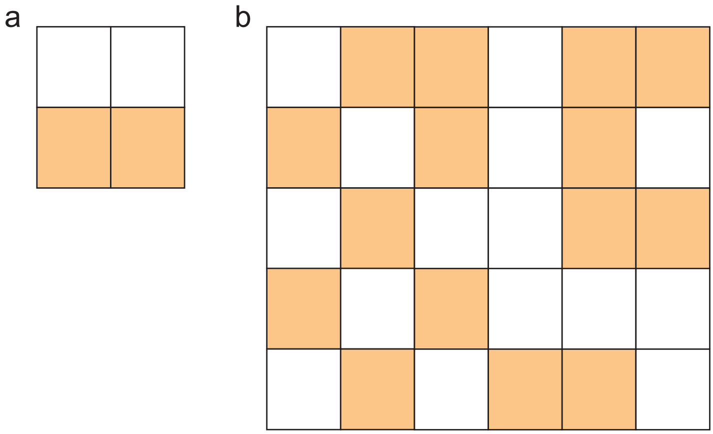


Fig. 2.6 Examples of (**a**) easy and (**b**) difficult trials of the Visual Patterns Test

appropriate for the spatial part of the visuospatial processor. An application of the Visual Patterns Test to science education was reported by Bauhoff et al. (2012) who investigated how performance on this test was related to visually detecting faulty pendulum clocks (see details in Castro-Alonso et al. this volume-b, Chap. 5).

The second instrument of this group is the Visual Span Test. It was originally developed by Ashkenazi and Shapira (2017). This instrument shows squares placed on the screen, similar to a computerized Corsi Block Tapping Test. However, it does not highlight the squares in sequences, but shows all simultaneously in different colors. The levels of difficulty range from two to nine colored squares. The task is to memorize the colors in all the positions and judge if a square changed color after a blank screen of a certain interval.

To mention two examples applying the Visual Span Test, Blacker et al. (2014) observed that performance on this instrument could be enhanced by action videogame training (see Castro-Alonso and Fiorella this volume, Chap. 6), but Harrison et al. (2013) reported that training in dual working memory tasks (see Sect. 2.3.6) did not enhance performance in a visual span test.

The last common instrument in this group, named the Grid Locations, was used by Berka et al. (2007). It shows square grids of 9–36 contained squares, in which randomly some of them include a mark, and participants must memorize the signaled positions.

The second category of visual working memory tests includes those that imply memorizing identity or position of objects. From the seven primary visual thinking abilities described by Thurstone (1950), the one called *visual memory* is the ability that later was termed *object identity memory*, to distinguish it from *object location memory*. Eals and Silverman (1994) measured both abilities in a study of university students given arrays with illustrated uncommon objects (see also Epting and Overman 1998).

In the Object Identity Memory task, a stimulus array of several illustrated objects was shown on paper before the test display, which contained more objects. Without watching the stimulus array, the task was to determine which were the added objects in the test array. In the Object Location Memory task, the test array contained the same objects as the stimulus array, but some were displaced. The task was to mark on the paper which objects stayed in position and which had been moved.

More current studies have used similar tasks of object locations (e.g., Choi and L'Hirondelle 2005; Hammond et al. 2019; Postma et al. 2004). In these tasks, participants must memorize arrays of images, and then from memory, attempt to place the pictures in the correct positions. To measure performance, typically a negative score of displacement or distance error is obtained by comparing the answered positions to the correct positions.

An interesting finding of these visual working memory instruments is the effect of gender or sex (see Castro-Alonso and Jansen this volume, Chap. 4): As compared to the other tasks described here (notably 3D mental rotation), which tend to be more favorable to men, Object Location Memory is usually outperformed by women (see Eals and Silverman 1994; Silverman et al. 2007; but see Postma et al. 2004).

As stated above, tests measuring mostly the visual subcomponent of visuospatial working memory can also be categorized as instruments of simultaneous (and not sequential) visual stimuli. Since these tests show stimuli where participants must not follow a given sequence, this freedom of choice could explain why visual working memory tests are generally easier than spatial working memory tests. In line with this difference, in three experiments with university students, Rudkin et al. (2007) reported that spatial tasks involving sequences (e.g., the Corsi Block Tapping Test) were more disrupted by concurrent central executive tasks, as compared to simultaneous visual tasks. In other words, since the spatial or sequential tasks are more challenging, they recruit more cognitive resources from the central executive, compared to the easier visual or simultaneous tasks.

2.3.6 Dual Visuospatial Tasks of Working Memory

Dual or complex working memory tasks include two tasks, a *memory task* that is interrupted by a *processing task*. In the memory task, different stimuli are shown in a specific order. The participants' job is to memorize the stimuli and the order in which the stimuli were presented. For example, the seminal study of dual tasks by Daneman and Carpenter (1980) incorporated the *Reading Span Task*, a verbal dual task in which the memory task involves remembering the last words of the sentences presented, and the processing task is to read or listen to following sentences. Thus, the memorization of the last words in every sentence is interrupted by reading or listening to new sentences. Rising in difficulty as the task progresses, the Reading Span Task typically starts with two sentences, and increases by one after every trial, to finish with a maximum of six sentences.

In addition to the Reading Span Task and other verbal tests, several visuospatial dual tasks have been developed, such as: (a) the *Counting Span* (e.g., Kane et al.

2004), (b) the *Rotation Span* (Shah and Miyake 1996), (c) the *Symmetry Span* (Kane et al. 2004), (d) the *Dot Matrix Task* (Law et al. 1995), and (e) the *Alignment Span* (Hale et al. 2011).

In the Counting Span task (e.g., Schmiedek et al. 2009), the memory task is to count and memorize the number of blue circles shown, in a display that also includes green circles and blue squares. The processing task involves judging if the number memorized is even or odd. In the Rotation Span (e.g., Foster et al. 2017; Miller and Halpern 2013), the memory stimuli comprise arrows in different rotations, usually in increments of 45°. The processing task involves determining if rotated (generally in steps of 45°) capital letters are normal or mirror-reversed.

In the Symmetry Span (e.g., Minear et al. 2016), the memory stimuli comprise patterns of empty squares in which, randomly, one square is filled in color (or includes a colored shape). The processing task usually involves determining if different patterns of squares are symmetrical or not. The Dot Matrix Task (e.g., Law et al. 1995; Miyake et al. 2001a; Örün and Akbulut 2019) has a memory component as that on the symmetry span, with patterns of colored squares or shapes, but it includes a different processing task, which involves estimating if dot matrix equations of additions and subtractions are correct or incorrect.

Lastly, the Alignment Span (e.g., Minear et al. 2016) also includes a memory task involving patterns of squares. The processing task is to judge if the colored shapes in the squares form a line or not. There are also examples of instruments that allow different combinations of memory and processing tasks (see, e.g., Castro-Alonso et al. this volume-a, Chap. 8; see also Castro-Alonso et al. 2018a).

When scoring dual visuospatial working memory tasks, Unsworth et al. (2005) recommended to include the performance of both the memory and the processing tasks, as this could give more information than solely considering the scores in the memory task. As such, we also recommend scoring: (a) the memory task, by summing each of the correctly recalled items (following the sequence order); and (b) the processing task, by summing each correctly answered processing item.

Much of the evidence for separate processing of verbal and visuospatial information in working memory has been obtained with studies employing dual visuospatial instruments, such as the two experiments reported by Shah and Miyake (1996). In Experiment 1, 54 undergraduates completed measures of both verbal and spatial ability (involving mental rotation and mental folding). Additionally, they completed two dual working memory tasks, a verbal and a visuospatial. It was observed that the correlation between verbal ability and the dual verbal task ($r = .45$) was significantly larger than that between the verbal ability and the visuospatial dual task ($r = .07$). In a similar way, the correlation between the composite spatial ability and the dual visuospatial task ($r = .66$) was significantly larger than that for the spatial ability and the dual verbal task ($r = .12$).

In Experiment 2 with 60 undergraduates, the results were replicated with novel verbal and visuospatial dual tasks. In addition, the authors compared the interferences in dual tasks when the memory task was either verbal or visuospatial and the interrupting processing task was also either verbal or visuospatial. Results showed a double dissociation: the score in the verbal dual task was lower when the interspaced processing task was verbal, as compared to visuospatial, whereas the score in the visuospatial dual task was lower when the processing task was visuospatial, as compared to verbal.

Further support for the verbal and visuospatial separability was provided by Hale et al. (2011) in a study with 388 adults attempting different verbal and visuospatial tasks, including dual complex tests. The authors concluded that the best fitting structural equation models for the results were those in which the verbal and visuospatial domains were separated.

While there is much supporting evidence for distinct verbal and spatial processes, there are some findings where the visuospatial and verbal formats are not as independent. For example, Vergauwe et al. (2010) randomly assigned 96 psychology undergraduates (91% females) to four experimental groups. The groups were obtained by crossing two memory task formats (verbal vs. visuospatial) and two processing task domains (verbal vs. visuospatial). It was observed that at the most challenging levels, both the verbal and the visuospatial processing tasks produced impairments to the verbal memory task. Similarly, both the most difficult verbal or visuospatial processing tasks impaired the visuospatial memory task.

In conclusion, although there is a separability between verbal and visuospatial processing, which can be observed in selective interferences in dual tasks, there is still some degree of overlapping between the formats, as they both share common working memory resources. As such, there are interferences between verbal and visuospatial tasks, although they are smaller than the interferences between, for example, visuospatial memory and visuospatial processing tasks.

2.4 Interactions Between Visuospatial Processing Abilities

As expected, although these visuospatial processing abilities are different, they tend to be associated because they all rely on the visuospatial sketch pad and the central executive of working memory. As summarized in Table 2.2, three research lines show associations between visuospatial processing tasks. Firstly, *correlational studies* show significant, and usually medium to large, correlations between the scores of different visuospatial processing tasks. Secondly, *selected samples* research involves selecting the top scorers in a visuospatial task in order to test them in another visuospatial task. The findings tend to show that these selected participants also perform well in the new task. Thirdly, the *transfer effect* studies show that training for a

Table 2.2 Research lines showing relationships between small-scale visuospatial processing tasks

Research line	Findings
Correlational studies	Medium to large correlations between visuospatial tasks
Selected samples	Top scorers in a visuospatial task are selected to perform in another visuospatial task, and they perform well in both
Transfer effects	Training certain visuospatial task also enhances another visuospatial task

visuospatial task or ability not only leads to improvement in that task but also in another visuospatial task (see also Castro-Alonso and Uttal this volume, Chap. 3).

Concerning correlations between the abilities, they are generally larger inside the same constructs. For example, large correlations can be observed for different instruments that measure mental rotation, and also large correlations are revealed among different tests of mental folding. Miyake et al. (2001a) reported that 167 undergraduate students showed a large correlation ($r = .67$, $p < .05$) between two different 2D mental rotation tests (the Card Rotations Test and the Flags Tests), and also a large correlation ($r = .71$, $p < .05$) between two mental folding tasks (including the Paper-Folding Test).

These correlations can also be observed between 2D and 3D mental rotation instruments. For example, in two experiments with undergraduate students, Hegarty and Waller (2004) reported medium correlations (all rs > .38, all ps < .01) between 3D and 2D mental rotation instruments (Mental Rotation Test, Cube Comparisons Test, Card Rotations Test, and Flags Test).

Also, several studies have shown correlations between different dual visuospatial tasks. For example, investigating 150 adults, Hale et al. (2011) reported large correlations (rs > .66) between three dual visuospatial working memory tests, including the Alignment Span. Somewhat smaller effects were observed by Schmiedek et al. (2009), who investigated 96 adult participants (47% females), and reported a medium sized correlation ($r = .28$, $p < .01$) between two dual visuospatial working memory tasks (Counting Span and Rotation Span).

Similarly, in a study with 116 university students (64% females), Minear et al. (2016) reported that the Symmetry Span was not correlated with the Rotation Span ($r = .14$), but that the Symmetry Span showed a medium correlation with the Alignment Span ($r = .32$, $p < .01$), and that the Rotation Span showed a medium to large correlation with the Alignment Span ($r = .38$, $p < .01$).

In addition to effects in the same construct, significant correlations can also be observed between different visuospatial tasks. For example, with a sample larger than 3,400 individuals aged 14–60, Vandenberg and Kuse (1978) reported medium to large correlations (all rs > .39) between tests of 3D mental rotation, 2D mental rotation, mental folding, and field independence. Similarly, in the study with 170 adults by Hunt et al. (1988), there were medium to large correlations (all rs > .45, all ps < .01) between instruments measuring 3D mental rotation, 2D mental rotation, and mental folding. Moreover, there were medium correlations (all rs > .25, all ps < .01) between these three pen-and-paper instruments and two computer tests, each recording 2D mental rotation and mental folding.

Atit et al. (2013) observed in 116 psychology undergraduates (67% females) a medium to large correlation ($r = .46$) between a 3D mental rotation test (the Mental Rotations Test) and a mental folding test (the Paper Folding Test). Allen et al. (1996) reported two experiments with a total of 203 participants (55% females). In both studies, medium to large correlations (all rs > .42) were observed between tests of 3D mental rotation (the Cube Comparisons Test), mental folding (the Surface Development Test), and field independence (the Hidden Figures Test). Also, in an experiment with 167 undergraduates, Miyake et al. (2001a) reported: (a) small to medium correlations (both rs > .22, $p < .05$) between two mental folding tasks (including the Paper-Folding Test) and a spatial working memory task (the Corsi Block Tapping Test); (b) medium correlations (both rs > .32, $p < .05$) between two 2D mental rotation tasks (the Card Rotations Test and the Flags Tests) and the spatial working memory test; and (c) medium correlations (all four rs > .39, $p < .05$) between these two 2D mental rotation tasks and the two mental folding tasks.

In the investigation with 116 participants by Minear et al. (2016), medium to large correlations (rs > .28, ps < .01) were found between a spatial working memory task (Object N-Back Task) and three dual working memory tests (Symmetry Span, Rotation Span, and Alignment Span). In their study with 96 adults (47% females), Schmiedek et al. (2009) observed a large correlation ($r = .51$, $p < .01$) between a dual task of working memory (Rotation Span) and a spatial working memory task (N-Back Task). Interestingly, another dual task (Counting Span), did not correlate significantly ($r = .17$) with the same spatial N-Back Task.

Addressing the research line of selected samples, Cornoldi and Mammarella (2008) measured the performance of psychology undergraduates on the Mental Rotations Test. From the test results, the authors selected the 20 students (90% females) who were the top 10% achievers, and the 20 participants (95% females) in the bottom 10%. Then, these 40 undergraduates attempted a spatial working memory task (the Corsi Block Tapping Test) in different formats, including forward and backward directions. When comparing performance in the Corsi Block Tapping Test between the top and bottom scorers of the Mental Rotations Test, it was observed that top mental rotators presented higher scores in the most demanding formats of the Corsi Block Tapping Test, that is, when it presented sequences of 5–6 and 7–8 blocks.

Foster et al. (2017) calculated a composite score with the data of adult participants in three dual tasks of working memory. From this global score, the authors selected those in the top and the bottom thirds. Top and bottom achievers were compared in a battery of 15 ability tests, including dual visuospatial tasks of working memory and the Paper Folding Test of mental folding. The top scorers in the dual tasks presented a significantly higher performance in other dual tasks and in the Paper Folding Test, compared to the low dual task achievers.

Considering investigations measuring transfer effects, Stericker and LeVesconte (1982) trained 45 psychology undergraduates (53% females) with three different tests, respectively measuring 3D mental rotation, mental folding, and field independence. After the six training sessions, besides the expected increase on the tasks, there was also a significantly higher performance on an untrained 2D mental rotation task.

Wright et al. (2008) investigated if mental rotation training could assist mental folding performance, and vice versa. In a study with 38 adults (47% females), the authors observed the expected higher performance after training, for both a 3D mental rotation task and a mental folding task with paper cubes. Interestingly, training in the mental rotation task was also productive for the mental folding task. An equivalent intermediate transfer effect was reported for the mental folding task affecting the mental rotation test.

Similarly, Stephenson and Halpern (2013) examined the effects of Spatial N-Back Task training on 3D mental rotation and mental folding in 29 adults (52% females). They observed that n-back was an effective visuospatial task to increase performance on both the mental rotation and the mental folding tests.

Nevertheless, there are studies failing to show transfer effects between different visuospatial tasks. For example, in an investigation with 24 adults (58% females), Redick et al. (2013) observed that training with a spatial and auditory n-back task was not effective for improving scores in mental folding or dual visuospatial working memory tasks. Similarly, with a sample of 69 adults (45% females), Schwarb et al. (2016) also showed that training with a Spatial N-Back Task did not enhance performance in a dual visuospatial task.

2.5 Discussion

In this review chapter, we described the subdivisions of working memory and concentrated on the visuospatial sketch pad and the central executive, as the processors of visuospatial information that allow performance on different tasks. A classification of these tasks discriminates between larger spatial abilities and small or object spatial abilities. Concentrating on the most relevant for education in health and natural sciences, we further described several small-scale spatial abilities and related tasks employing visual and spatial working memory. We presented various common tests to measure these abilities. Lastly, based on the results of three research lines, namely correlational studies, selected samples, and transfer effects, we showed that the small-scale visuospatial abilities were interrelated.

2.5.1 Instructional Implications for Health and Natural Sciences

A first instructional implication of this chapter is to foster visuospatial processing in science students. A strategy to attain this is to stimulate visuospatial processing in science classes by including activities that trigger the visuospatial working memory, such as visualization of relationships between science depictions, predicting the behavior of objects in static and dynamic systems, transforming visuospatial information, and employing models to manipulate science depictions.

A second implication, arguably the most important, is that different small-scale visuospatial abilities will be more or less suitable for different science learning scenarios. For example, mental rotation seems to be more critical for chemistry exams that imply the rotation of molecules. Field independence could be more effective when working with microscopic preparations in biology. Consequently, it will be beneficial to consider these abilities separately, instead of integrating them in an overall spatial ability construct.

2.5.2 Future Research Directions

As criticized by Darling et al. (2006), sometimes the distinction between a visual and a spatial working memory tests is also a distinction between a simultaneous and a sequential presentation of visual stimuli. In other words, some tests confound the properties of *visual* with *simultaneous*, and similarly, others do not discriminate between *spatial* and *sequential*. Novel tests should measure separately the visual and the simultaneous, or the spatial and the sequential properties of visuospatial working memory. Future directions of research with these four separate properties for testing may provide evidence to support which of them is a better resource to learn certain science topics.

Small-scale visuospatial abilities require visuospatial processing of working memory, but there are also different strategies to deal with the tests presented in this chapter. For example, Hegarty (2018) reported more and less effective strategies that university students used to answer the Mental Rotations Test. Future research should investigate not only performance on visuospatial processing tests, but also the strategies used to solve these tests.

Although we provided the most common visuospatial abilities investigated in university education concerning health and natural sciences, other visuospatial abilities and tests were not included in this chapter. Future research could show interactions between the abilities in this chapter and some other skills, such as those required for dynamic (e.g., Sanchez and Wiley 2014), large-scale (e.g., Hegarty et al. 2006) or non-rigid (e.g., Atit et al. 2013) spatial transformations.

2.5.3 Conclusion

Visuospatial processing of working memory controls different abilities. Several of the small-scale abilities controlled by this cognitive processor—including mental rotation, mental folding, field independence, visual working memory, spatial working memory, and dual visuospatial working memory—can be beneficial to learn concepts about health and natural sciences. Knowing the differences and similarities between these abilities will help future research about its specific features and which of these characteristics could be the most suitable for a given instructional task within science education.

Acknowledgments Support from PIA-CONICYT Basal Funds for Centers of Excellence Project FB0003 is gratefully acknowledged. The first author is thankful to Enrique Castro and Mariana Poblete for their assistance.

References

Aldahmash, A. H., & Abraham, M. R. (2009). Kinetic versus static visuals for facilitating college students' understanding of organic reaction mechanisms in chemistry. *Journal of Chemical Education, 86*(12), 1442–1446. https://doi.org/10.1021/ed086p1442.

Allen, G. L., Kirasic, K. C., Dobson, S. H., Long, R. G., & Beck, S. (1996). Predicting environmental learning from spatial abilities: An indirect route. *Intelligence, 22*(3), 327–355. https://doi.org/10.1016/S0160-2896(96)90026-4.

Ashkenazi, S., & Shapira, S. (2017). Number line estimation under working memory load: Dissociations between working memory subsystems. *Trends in Neuroscience and Education, 8–9*, 1–9. https://doi.org/10.1016/j.tine.2017.09.001.

Atit, K., Shipley, T. F., & Tikoff, B. (2013). Twisting space: Are rigid and non-rigid mental transformations separate spatial skills? *Cognitive Processing, 14*(2), 163–173. https://doi.org/10.1007/s10339-013-0550-8.

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556–559.

Bauhoff, V., Huff, M., & Schwan, S. (2012). Distance matters: Spatial contiguity effects as trade-off between gaze switches and memory load. *Applied Cognitive Psychology, 26*(6), 863–871. https://doi.org/10.1002/acp.2887.

Berka, C., Levendowski, D. J., Lumicao, M. N., Yau, A., Davis, G., Zivkovic, V. T., et al. (2007). EEG correlates of task engagement and mental workload in vigilance, learning, and memory tasks. *Aviation, Space, and Environmental Medicine, 78*(5), B231–B244.

Berney, S., Bétrancourt, M., Molinari, G., & Hoyek, N. (2015). How spatial abilities and dynamic visualizations interplay when learning functional anatomy with 3D anatomical models. *Anatomical Sciences Education, 8*(5), 452–462. https://doi.org/10.1002/ase.1524.

Bethell-Fox, C. E., & Shepard, R. N. (1988). Mental rotation: Effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 14*(1), 12–23. https://doi.org/10.1037/0096-1523.14.1.12.

Blacker, K. J., Curby, K. M., Klobusicky, E., & Chein, J. M. (2014). Effects of action video game training on visual working memory. *Journal of Experimental Psychology. Human Perception and Performance, 40*(5), 1992–2004. https://doi.org/10.1037/a0037556.

Bodner, G. M., & Guay, R. B. (1997). The Purdue Visualization of Rotations Test. *The Chemical Educator, 2*(4), 1–17. https://doi.org/10.1007/s00897970138a.

Bruyer, R., & Scailquin, J.-C. (1998). The visuospatial sketchpad for mental images: Testing the multicomponent model of working memory. *Acta Psychologica, 98*(1), 17–36. https://doi.org/10.1016/S0001-6918(97)00053-X.

Buckley, J., Seery, N., & Canty, D. (2018). A heuristic framework of spatial ability: A review and synthesis of spatial factor literature to support its translation into STEM education. *Educational Psychology Review, 30*(3), 947–972. https://doi.org/10.1007/s10648-018-9432-z.

Castro-Alonso, J. C., & Fiorella, L. (this volume). Interactive science multimedia and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 145–173). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_6.

Castro-Alonso, J. C., & Jansen, P. (this volume). Sex differences in visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 81–110). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_4.

Castro-Alonso, J. C., & Uttal, D. H. (2019). Spatial ability for university biology education. In S. Nazir, A.-M. Teperi, & A. Polak-Sopińska (Eds.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2018 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 283–291). Cham: Springer. https://doi.org/10.1007/978-3-319-93882-0_28.

Castro-Alonso, J. C., & Uttal, D. H. (this volume). Science education and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 53–79). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_3.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2014). Learning from observing hands in static and animated versions of non-manipulative tasks. *Learning and Instruction, 34*, 11–21. https://doi.org/10.1016/j.learninstruc.2014.07.005.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018a). Computerized and adaptable tests to measure visuospatial abilities in STEM students. In T. Andre (Ed.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2017 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 337–349). Cham: Springer. https://doi.org/10.1007/978-3-319-60018-5_33.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2018b). Learning symbols from permanent and transient visual presentations: Don't overplay the hand. *Computers & Education, 116*, 1–13. https://doi.org/10.1016/j.compedu.2017.08.011.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (this volume-a). VAR: A battery of computer-based instruments to measure visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 207–229). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_8.

Castro-Alonso, J. C., Ayres, P., & Sweller, J. (this volume-b). Instructional visualizations, cognitive load theory, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 111–143). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_5.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (this volume-c). Embodied cognition, science education, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 175–205). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_7.

Choi, J., & L'Hirondelle, N. (2005). Object location memory: A direct test of the verbal memory hypothesis. *Learning and Individual Differences, 15*(3), 237–245. https://doi.org/10.1016/j.lindif.2005.02.001.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale: Erlbaum.

Cornoldi, C., & Mammarella, I. C. (2008). A comparison of backward and forward spatial spans. *The Quarterly Journal of Experimental Psychology, 61*(5), 674–682. https://doi.org/10.1080/17470210701774200.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*(4), 450–466. https://doi.org/10.1016/S0022-5371(80)90312-6.

Darling, S., Della Sala, S., Logie, R. H., & Cantagallo, A. (2006). Neuropsychological evidence for separating components of visuo–spatial working memory. *Journal of Neurology, 253*(2), 176–180. https://doi.org/10.1007/s00415-005-0944-3.

Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwelding visuo–spatial memory. *Neuropsychologia, 37*(10), 1189–1199. https://doi.org/10.1016/S0028-3932(98)00159-6.

Eals, M., & Silverman, I. (1994). The Hunter-Gatherer theory of spatial sex differences: Proximate factors mediating the female advantage in recall of object arrays. *Ethology and Sociobiology, 15*(2), 95–105. https://doi.org/10.1016/0162-3095(94)90020-5.

Eitel, A., Bender, L., & Renkl, A. (2019). Are seductive details seductive only when you think they are relevant? An experimental test of the moderating role of perceived relevance. *Applied Cognitive Psychology, 33*(1), 20–30. https://doi.org/10.1002/acp.3479.

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Kit of factor-referenced cognitive tests*. Princeton: Educational Testing Service.

Epting, L. K., & Overman, W. H. (1998). Sex-sensitive tasks in men and women: A search for performance fluctuations across the menstrual cycle. *Behavioral Neuroscience, 112*(6), 1304–1317. https://doi.org/10.1037/0735-7044.112.6.1304.

Fiorella, L., & Mayer, R. E. (2017). Spontaneous spatial strategy use in learning from scientific text. *Contemporary Educational Psychology, 49*, 66–79. https://doi.org/10.1016/j.cedpsych.2017.01.002.

Foster, J. L., Harrison, T. L., Hicks, K. L., Draheim, C., Redick, T. S., & Engle, R. W. (2017). Do the effects of working memory training depend on baseline ability level? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*(11), 1677–1689. https://doi.org/10.1037/xlm0000426.

Garg, A. X., Norman, G., & Sperotable, L. (2001). How medical students learn spatial anatomy. *The Lancet, 357*(9253), 363–364. https://doi.org/10.1016/S0140-6736(00)03649-7.

Gibbons, R. D., Baker, R. J., & Skinner, D. B. (1986). Field articulation testing: A predictor of technical skills in surgical residents. *Journal of Surgical Research, 41*(1), 53–57. https://doi.org/10.1016/0022-4804(86)90008-9.

Gold, A. U., Pendergast, P. M., Ormand, C. J., Budd, D. A., & Mueller, K. J. (2018). Improving spatial thinking skills among undergraduate geology students through short online training exercises. *International Journal of Science Education, 40*(18), 2205–2225. https://doi.org/10.1080/09500693.2018.1525621.

Hale, S., Rose, N. S., Myerson, J., Strube, M. J., Sommers, M., Tye-Murray, N., et al. (2011). The structure of working memory abilities across the adult life span. *Psychology and Aging, 26*(1), 92–110. https://doi.org/10.1037/a0021483.

Hambrick, D. Z., Libarkin, J. C., Petcovic, H. L., Baker, K. M., Elkins, J., Callahan, C. N., et al. (2012). A test of the circumvention-of-limits hypothesis in scientific problem solving: The case of geological bedrock mapping. *Journal of Experimental Psychology: General, 141*(3), 397–403. https://doi.org/10.1037/a0025927.

Hammond, A. G., Murphy, E. M., Silverman, B. M., Bernas, R. S., & Nardi, D. (2019). No environmental context-dependent effect, but interference, of physical activity on object location memory. *Cognitive Processing, 20*(1), 31–43. https://doi.org/10.1007/s10339-018-0875-4.

Harrison, T. L., Shipstead, Z., Hicks, K. L., Hambrick, D. Z., Redick, T. S., & Engle, R. W. (2013). Working memory training may increase working memory capacity but not fluid intelligence. *Psychological Science, 24*(12), 2409–2419. https://doi.org/10.1177/0956797613492984.

Hausmann, M., Schoofs, D., Rosenthal, H. E. S., & Jordan, K. (2009). Interactive effects of sex hormones and gender stereotypes on cognitive sex differences—A psychobiosocial approach. *Psychoneuroendocrinology, 34*(3), 389–401. https://doi.org/10.1016/j.psyneuen.2008.09.019.

Hautzel, H., Mottaghy, F. M., Schmidt, D., Zemb, M., Shah, N. J., Müller-Gärtner, H.-W., et al. (2002). Topographic segregation and convergence of verbal, object, shape and spatial working memory in humans. *Neuroscience Letters, 323*(2), 156–160. https://doi.org/10.1016/S0304-3940(02)00125-8.

Hegarty, M. (2018). Ability and sex differences in spatial thinking: What does the mental rotation test really measure? *Psychonomic Bulletin & Review, 25*(3), 1212–1219. https://doi.org/10.3758/s13423-017-1347-z.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32*(2), 175–191. https://doi.org/10.1016/j.intell.2003.12.001.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34*(2), 151–176. https://doi.org/10.1016/j.intell.2005.09.005.

Hegarty, M., Keehner, M., Khooshabeh, P., & Montello, D. R. (2009). How spatial abilities enhance, and are enhanced by, dental education. *Learning and Individual Differences, 19*(1), 61–70. https://doi.org/10.1016/j.lindif.2008.04.006.

Heil, M., & Jansen-Osmann, P. (2008). Sex differences in mental rotation with polygons of different complexity: Do men utilize holistic processes whereas women prefer piecemeal ones? *The Quarterly Journal of Experimental Psychology, 61*(5), 683–689. https://doi.org/10.1080/17470210701822967.

Hinze, S. R., Williamson, V. M., Shultz, M. J., Williamson, K. C., Deslongchamps, G., & Rapp, D. N. (2013). When do spatial abilities support student comprehension of STEM visualizations? *Cognitive Processing, 14*(2), 129–142. https://doi.org/10.1007/s10339-013-0539-3.

Huk, T., & Steinke, M. (2007). Learning cell biology with close-up views or connecting lines: Evidence for the structure mapping effect. *Computers in Human Behavior, 23*(3), 1089–1104. https://doi.org/10.1016/j.chb.2006.10.004.

Huk, T., Steinke, M., & Floto, C. (2010). The educational value of visual cues and 3D-representational format in a computer animation under restricted and realistic conditions. *Instructional Science, 38*(5), 455–469. https://doi.org/10.1007/s11251-009-9116-7.

Hunt, E. B., Pellegrino, J. W., Frick, R. W., Farr, S. A., & Alderton, D. (1988). The ability to reason about movement in the visual field. *Intelligence, 12*(1), 77–100. https://doi.org/10.1016/0160-2896(88)90024-4.

Hyun, J.-S., & Luck, S. J. (2007). Visual working memory as the substrate for mental rotation. *Psychonomic Bulletin & Review, 14*(1), 154–158. https://doi.org/10.3758/BF03194043.

Imhof, B., Scheiter, K., Edelmann, J., & Gerjets, P. (2013). Learning about locomotion patterns: Effective use of multiple pictures and motion-indicating arrows. *Computers & Education, 65*, 45–55. https://doi.org/10.1016/j.compedu.2013.01.017.

Jang, S., Vitale, J. M., Jyung, R. W., & Black, J. B. (2017). Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. *Computers & Education, 106*, 150–165. https://doi.org/10.1016/j.compedu.2016.12.009.

Jaušovec, N., & Jaušovec, K. (2012). Working memory training: Improving intelligence – Changing brain activity. *Brain and Cognition, 79*(2), 96–106. https://doi.org/10.1016/j.bandc.2012.02.007.

Kail, R. (1986). The impact of extended practice on rate of mental rotation. *Journal of Experimental Child Psychology, 42*(3), 378–391. https://doi.org/10.1016/0022-0965(86)90032-9.

Kalet, A. L., Song, H. S., Sarpel, U., Schwartz, R. N., Brenner, J., Ark, T. K., et al. (2012). Just enough, but not too much interactivity leads to better clinical skills performance after a computer assisted learning module. *Medical Teacher, 34*(10), 833–839. https://doi.org/10.3109/0142159X.2012.706727.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General, 133*(2), 189–217. https://doi.org/10.1037/0096-3445.133.2.189.

Keehner, M., Tendick, F., Meng, M. V., Anwar, H. P., Hegarty, M., Stoller, M. L., et al. (2004). Spatial ability, experience, and skill in laparoscopic surgery. *The American Journal of Surgery, 188*(1), 71–75. https://doi.org/10.1016/j.amjsurg.2003.12.059.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352–358. https://doi.org/10.1037/h0043688.

Könen, T., Strobach, T., & Karbach, J. (2016). Working memory. In T. Strobach & J. Karbach (Eds.), *Cognitive training: An overview of features and applications* (pp. 59–68). Cham: Springer. https://doi.org/10.1007/978-3-319-42662-4_6.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition, 29*(5), 745–756. https://doi.org/10.3758/bf03200477.

Kozhevnikov, M., & Thornton, R. (2006). Real-time data display, spatial visualization ability, and learning force and motion concepts. *Journal of Science Education and Technology, 15*(1), 111–132. https://doi.org/10.1007/s10956-006-0361-0.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science, 31*(4), 549–579. https://doi.org/10.1080/15326900701399897.

Kozhevnikov, M., Blazhenkova, O., & Becker, M. (2010). Trade-off in object versus spatial visualization abilities: Restriction in the development of visual-processing resources. *Psychonomic Bulletin & Review, 17*(1), 29–35. https://doi.org/10.3758/pbr.17.1.29.

Kozhevnikov, M., Schloerb, D. W., Blazhenkova, O., Koo, S., Karimbux, N., Donoff, R. B., et al. (2013). Egocentric versus allocentric spatial ability in dentistry and haptic virtual reality training. *Applied Cognitive Psychology, 27*(3), 373–383. https://doi.org/10.1002/acp.2915.

Kühl, T., Stebner, F., Navratil, S. C., Fehringer, B. C. O. F., & Münzer, S. (2018). Text information and spatial abilities in learning with different visualizations formats. *Journal of Educational Psychology, 110*(4), 561–577. https://doi.org/10.1037/edu0000226.

Law, D. J., Morrin, K. A., & Pellegrino, J. W. (1995). Training effects and working memory contributions to skill acquisition in a complex coordination task. *Learning and Individual Differences, 7*(3), 207–234. https://doi.org/10.1016/1041-6080(95)90011-X.

Lee, D. Y., & Shin, D.-H. (2011). Effects of spatial ability and richness of motion cue on learning in mechanically complex domain. *Computers in Human Behavior, 27*(5), 1665–1674. https://doi.org/10.1016/j.chb.2011.02.005.

Lejbak, L., Crossley, M., & Vrbancic, M. (2011). A male advantage for spatial and object but not verbal working memory using the n-back task. *Brain and Cognition, 76*(1), 191–196. https://doi.org/10.1016/j.bandc.2010.12.002.

Linn, M. C., & Kyllonen, P. (1981). The field dependence–independence construct: Some, one, or none. *Journal of Educational Psychology, 73*(2), 261–273. https://doi.org/10.1037/0022-0663.73.2.261.

Lord, T. R. (1990). Enhancing learning in the life sciences through spatial perception. *Innovative Higher Education, 15*(1), 5–16. https://doi.org/10.1007/BF00889733.

McEvoy, L. K., Smith, M. E., & Gevins, A. (1998). Dynamic cortical networks of verbal and spatial working memory: Effects of memory load and task practice. *Cerebral Cortex, 8*(7), 563–574. https://doi.org/10.1093/cercor/8.7.563.

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin, 86*(5), 889–918. https://doi.org/10.1037/0033-2909.86.5.889.

McGrew, K. S. (2009). CHC theory and the human cognitive abilities project: Standing on the shoulders of the giants of psychometric intelligence research. *Intelligence, 37*(1), 1–10. https://doi.org/10.1016/j.intell.2008.08.004.

Michael, W. B., Guilford, J. P., Fruchter, B., & Zimmerman, W. S. (1957). The description of spatial-visualization abilities. *Educational and Psychological Measurement, 17*(2), 185–199. https://doi.org/10.1177/001316445701700202.

Miller, D. I., & Halpern, D. F. (2013). Can spatial training improve long-term outcomes for gifted STEM undergraduates? *Learning and Individual Differences, 26*, 141–152. https://doi.org/10.1016/j.lindif.2012.03.012.

Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27*(3), 272–277.

Minear, M., Brasher, F., Guerrero, C. B., Brasher, M., Moore, A., & Sukeena, J. (2016). A simultaneous examination of two forms of working memory training: Evidence for near transfer only. *Memory & Cognition, 44*(7), 1014–1037. https://doi.org/10.3758/s13421-016-0616-9.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001a). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General, 130*(4), 621–640. https://doi.org/10.1037//0096-3445.130.4.621.

Miyake, A., Witzki, A. H., & Emerson, M. J. (2001b). Field dependence–independence from a working memory perspective: A dual-task investigation of the Hidden Figures Test. *Memory, 9*(4–6), 445–457. https://doi.org/10.1080/09658210143000029.

Ness, D., Farenga, S. J., & Garofalo, S. G. (2017). *Spatial intelligence: Why it matters from birth through the lifespan*. New York: Routledge.

Örün, Ö., & Akbulut, Y. (2019). Effect of multitasking, physical environment and electroencephalography use on cognitive load and retention. *Computers in Human Behavior, 92*, 216–229. https://doi.org/10.1016/j.chb.2018.11.027.

Pearson, J. L., & Ialongo, N. S. (1986). The relationship between spatial ability and environmental knowledge. *Journal of Environmental Psychology, 6*(4), 299–304. https://doi.org/10.1016/S0272-4944(86)80003-2.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*(1), 39–58. https://doi.org/10.1006/brcg.1995.1032.

Phillips, W. A., & Baddeley, A. (1971). Reaction time and short-term visual memory. *Psychonomic Science, 22*(2), 73–74. https://doi.org/10.3758/BF03332500.

Piburn, M. D., Reynolds, S. J., McAuliffe, C., Leedy, D. E., Birk, J. P., & Johnson, J. K. (2005). The role of visualization in learning from computer-based images. *International Journal of Science Education, 27*(5), 513–527. https://doi.org/10.1080/09500690412331314478.

Pilegard, C., & Mayer, R. E. (2018). Game over for Tetris as a platform for cognitive skill training. *Contemporary Educational Psychology, 54*, 29–41. https://doi.org/10.1016/j.cedpsych.2018.04.003.

Postma, A., Jager, G., Kessels, R. P. C., Koppeschaar, H. P. F., & van Honk, J. (2004). Sex differences for selective forms of spatial memory. *Brain and Cognition, 54*(1), 24–34. https://doi.org/10.1016/S0278-2626(03)00238-0.

Pribyl, J. R., & Bodner, G. M. (1987). Spatial ability and its role in organic chemistry: A study of four organic courses. *Journal of Research in Science Teaching, 24*(3), 229–240. https://doi.org/10.1002/tea.3660240304.

Provo, J., Lamar, C., & Newby, T. (2002). Using a cross section to train veterinary students to visualize anatomical structures in three dimensions. *Journal of Research in Science Teaching, 39*(1), 10–34. https://doi.org/10.1002/tea.10007.

Redick, T. S., Shipstead, Z., Harrison, T. L., Hicks, K. L., Fried, D. E., Hambrick, D. Z., et al. (2013). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology: General, 142*(2), 359–379. https://doi.org/10.1037/a0029082.

Resnick, I., & Shipley, T. F. (2013). Breaking new ground in the mind: An initial study of mental brittle transformation and mental rigid rotation in science experts. *Cognitive Processing, 14*(2), 143–152. https://doi.org/10.1007/s10339-013-0548-2.

Resnick, S. M., Berenbaum, S. A., Gottesman, I. I., & Bouchard, T. J. (1986). Early hormonal influences on cognitive functioning in congenital adrenal hyperplasia. *Developmental Psychology, 22*(2), 191–198. https://doi.org/10.1037/0012-1649.22.2.191.

Rudkin, S. J., Pearson, D. G., & Logie, R. H. (2007). Executive processes in visual and spatial working memory tasks. *The Quarterly Journal of Experimental Psychology, 60*(1), 79–100. https://doi.org/10.1080/17470210600587976.

Ruisoto, P., Juanes, J. A., & Prats, A. (2014). Enhancing neuroanatomy education using computer-based instructional material. *Computers in Human Behavior, 31*, 446–452. https://doi.org/10.1016/j.chb.2013.03.005.

Sanchez, C. A. (2012). Enhancing visuospatial performance through video game training to increase learning in visuospatial science domains. *Psychonomic Bulletin & Review, 19*(1), 58–65. https://doi.org/10.3758/s13423-011-0177-7.

Sanchez, C. A., & Wiley, J. (2014). The role of dynamic spatial ability in geoscience text comprehension. *Learning and Instruction, 31*, 33–45. https://doi.org/10.1016/j.learninstruc.2013.12.007.

Sanchez, C. A., & Wiley, J. (2017). Dynamic visuospatial ability and learning from dynamic visualizations. In R. Lowe & R. Ploetzner (Eds.), *Learning from dynamic visualization: Innovations in research and application* (pp. 155–176). Cham: Springer. https://doi.org/10.1007/978-3-319-56204-9_7.

Schmiedek, F., Hildebrandt, A., Lövdén, M., Wilhelm, O., & Lindenberger, U. (2009). Complex span versus updating tasks of working memory: The gap is not that deep. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(4), 1089–1096. https://doi.org/10.1037/a0015730.

Schwarb, H., Nail, J., & Schumacher, E. H. (2016). Working memory training improves visual short-term memory capacity. *Psychological Research, 80*(1), 128–148. https://doi.org/10.1007/s00426-015-0648-y.

Seufert, T., Schütze, M., & Brünken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude-treatment-interaction study. *Learning and Instruction, 19*(1), 28–42. https://doi.org/10.1016/j.learninstruc.2008.01.002.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General, 125*(1), 4–27. https://doi.org/10.1037/0096-3445.125.1.4.

Shepard, R. N., & Feng, C. (1972). A chronometric study of mental paper folding. *Cognitive Psychology, 3*(2), 228–243. https://doi.org/10.1016/0010-0285(72)90005-9.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701–703. https://doi.org/10.2307/1731476.

Silverman, I., Choi, J., & Peters, M. (2007). The hunter-gatherer theory of sex differences in spatial abilities: Data from 40 countries. *Archives of Sexual Behavior, 36*(2), 261–268. https://doi.org/10.1007/s10508-006-9168-6.

Smirni, P., Villardita, C., & Zappalà, G. (1983). Influence of different paths on spatial memory performance in the Block-Tapping Test. *Journal of Clinical Neuropsychology, 5*(4), 355–359. https://doi.org/10.1080/01688638308401184.

Stephenson, C. L., & Halpern, D. F. (2013). Improved matrix reasoning is limited to training on tasks with a visuospatial component. *Intelligence, 41*(5), 341–357. https://doi.org/10.1016/j.intell.2013.05.006.

Stericker, A., & LeVesconte, S. (1982). Effect of brief training on sex-related differences in visual–spatial skill. *Journal of Personality and Social Psychology, 43*(5), 1018–1029. https://doi.org/10.1037/0022-3514.43.5.1018.

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction, 17*(2), 219–234. https://doi.org/10.1016/j.learninstruc.2007.01.012.

Stull, A. T., Hegarty, M., & Mayer, R. E. (2009). Getting a handle on learning anatomy with interactive three-dimensional graphics. *Journal of Educational Psychology, 101*(4), 803–816. https://doi.org/10.1037/a0016849.

Stull, A. T., Fiorella, L., Gainer, M. J., & Mayer, R. E. (2018). Using transparent whiteboards to boost learning from online STEM lectures. *Computers & Education, 120*, 146–159. https://doi.org/10.1016/j.compedu.2018.02.005.

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology, 22*(7), 996–1013. https://doi.org/10.1002/acp.1420.

Thurstone, L. L. (1950). Some primary abilities in visual thinking. *Proceedings of the American Philosophical Society, 94*(6), 517–521.

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*(3), 498–505. https://doi.org/10.3758/bf03192720.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., et al. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352–402. https://doi.org/10.1037/a0028446.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*(2), 599–604. https://doi.org/10.2466/pms.1978.47.2.599.

Vandierendonck, A., Kemps, E., Fastame, M. C., & Szmalec, A. (2004). Working memory components of the Corsi blocks task. *British Journal of Psychology, 95*(1), 57–79. https://doi.org/10.1348/000712604322779460.

Vecchi, T., & Richardson, J. T. E. (2001). Measures of visuospatial short-term memory: The Knox Cube Imitation Test and the Corsi Blocks Test compared. *Brain and Cognition, 46*(1), 291–295. https://doi.org/10.1016/S0278-2626(01)80086-5.

Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science, 21*(3), 384–390. https://doi.org/10.1177/0956797610361340.

Wang, L., Cohen, A. S., & Carr, M. (2014). Spatial ability at two scales of representation: A meta-analysis. *Learning and Individual Differences, 36*, 140–144. https://doi.org/10.1016/j.lindif.2014.10.006.

Wanzel, K. R., Hamstra, S. J., Anastakis, D. J., Matsumoto, E. D., & Cusimano, M. D. (2002). Effect of visual-spatial ability on learning of spatially-complex surgical skills. *The Lancet, 359*(9302), 230–231. https://doi.org/10.1016/S0140-6736(02)07441-X.

Wiegmann, D. A., Dansereau, D. F., McCagg, E. C., Rewey, K. L., & Pitre, U. (1992). Effects of knowledge map characteristics on information processing. *Contemporary Educational Psychology, 17*(2), 136–155. https://doi.org/10.1016/0361-476X(92)90055-4.

Wiley, J. (2019). Picture this! Effects of photographs, diagrams, animations, and sketching on learning and beliefs about learning from a geoscience text. *Applied Cognitive Psychology, 33*(1), 9–19. https://doi.org/10.1002/acp.3495.

Wilson, L., Scott, J. H., & Power, K. G. (1987). Developmental differences in the span of visual memory for pattern. *British Journal of Developmental Psychology, 5*(3), 249–255. https://doi.org/10.1111/j.2044-835X.1987.tb01060.x.

Witkin, H. A. (1949). The nature and importance of individual differences in perception. *Journal of Personality, 18*(2), 145–170. https://doi.org/10.1111/j.1467-6494.1949.tb01237.x.

Wong, M., Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018). Investigating gender and spatial measurements in instructional animation research. *Computers in Human Behavior, 89*, 446–456. https://doi.org/10.1016/j.chb.2018.02.017.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review, 15*(4), 763–771. https://doi.org/10.3758/PBR.15.4.763.

Chapter 3
Science Education and Visuospatial Processing

Juan C. Castro-Alonso and David H. Uttal

Success in the disciplines of health and natural sciences requires many different cognitive abilities, including verbal, social, mathematical, and visuospatial abilities (cf. Halpern et al. 2007). The focus of this chapter is on the importance of visuospatial abilities in learning and thriving in science (see Wai et al. 2009; see also Khine 2017; Stieff and Uttal 2015).

There are two critical reasons why visuospatial processing is required to succeed in health and natural sciences. The first is that science phenomena are typically described and explained with visuospatial representations. For example, Mathewson (1999) reported core visuospatial representations that are shared among diverse scientific disciplines to explain phenomena of their concern (see also Mathewson 2005). The visuospatial representation of a *boundary*, for example, is employed in different scientific disciplines. In the discipline of botany, a boundary is shown to describe and explain a chloroplast membrane; in oceanography, it depicts the ocean surface. Four of these visuospatial representations shared by the sciences are shown in Fig. 3.1. A more detailed description of these and other representations from different health and natural sciences is given in Table 3.1.

The second reason why visuospatial processing is a requirement for science is that communication among science professionals often depends on visual and spatial information. Examples of these communicative tools are (see Mathewson 1999, 2005):

- data display: chart, graph, map, table, scale;
- data manipulation: comparison, conversion, distortion, extrapolation;
- ordering: category, hierarchy, timeline;

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

D. H. Uttal
School of Education and Social Policy, Northwestern University, Evanston, IL, USA

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_3

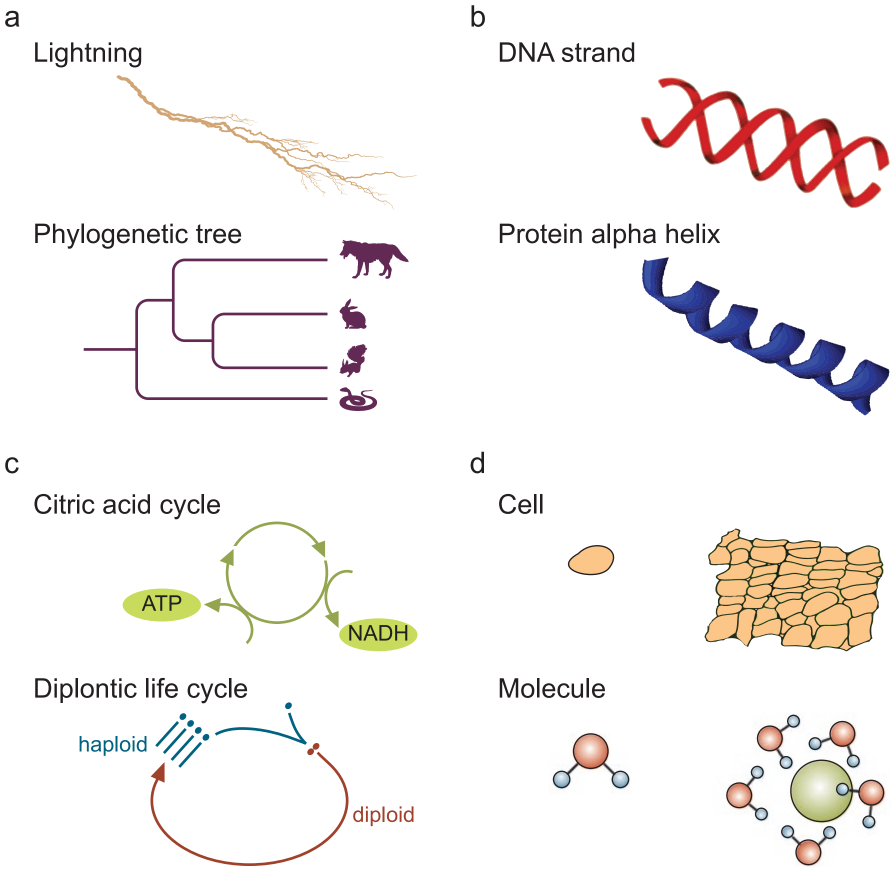


Fig. 3.1 Four core scientific visuospatial representations and examples of how they are instantiated in diverse science disciplines. The representations are (**a**) branching, (**b**) coil, (**c**) cycle, and (**d**) unit

- perceptual extension: magnification, scanning, time-lapse; and
- sign: code, icon, index, symbol.

In short, visuospatial processing is key for achievement in health and natural sciences. The main goal of this chapter is to show that importance. In the first sections of this chapter we provide evidence of two directions of effects between visuospatial processing and science education (see also Castro-Alonso and Uttal 2019): (a) visuospatial processing is an aid to learn science topics (Sect. 3.1), and (b) becoming more knowledgeable in science topics can help performance on visuospatial tasks (Sect. 3.2). In Sect. 3.3, we describe the potential of visuospatial training as a likely strategy to enhance learning and succeeding in the science disciplines. We end the chapter by discussing instructional implications and future directions for this reciprocal link between visuospatial processing and science performance.

Table 3.1 Common visuospatial representations and examples of how they are instantiated in different science disciplines

Common representation	Science discipline	Example
Boundary	Botany	Chloroplast membrane
	Meteorology, oceanography	Ocean surface
Branching	Meteorology	Lightning
	Botany, microbiology, zoology	Phylogenetic tree
Coil	Biology, genetics	DNA strand
	Biochemistry, genetics	Protein alpha helix
Circuit	Anatomy, physiology, zoology	Circulatory system
	Electrochemistry, physics	Electrical battery
Cycle	Biochemistry, physiology	Citric acid cycle
	Biology, botany, zoology	Diplontic life cycle
	Ecology, meteorology	Water cycle
Gradient	Cellular biology, neurology	Membrane potential
Group	Ecology	Population
Path	Astronomy	Planetary orbit
	Oceanography	Tidal current
Structure	Anatomy, zoology	Body plan
Unit	Biology, cellular biology	Cell
	Bioengineering, genetics	Codon
	Chemistry	Molecule

3.1 Visuospatial Processing Influencing Science Learning and Achievement

Results from different tests illustrate the importance of visuospatial processing in learning and succeeding in health and natural sciences. Details of most of the visuospatial tests described in this chapter can be found in Castro-Alonso and Atit (this volume, Chap. 2), and also in Castro-Alonso et al. (this volume-a, Chap. 8) and Castro-Alonso et al. (2018a).

Table 3.2 Examples of science areas and learning topics where different visuospatial abilities have been effective

Science area	Learning topic	Visuospatial ability
Anatomy	Hand bones	3D mental rotation
Anatomy	Gross anatomy	3D mental rotation
Medicine	Respiratory system	2D mental rotation and mental folding
Medicine	Autonomic nervous system	Field independence
Surgery	Laparoscopic skills	3D mental rotation and field independence
Surgery	Surgical skills	Mental folding
Biology	Classification of plants	Mental rotation and field independence
Biology	Functioning of an enzyme	2D mental rotation and mental folding
Chemistry	Organic chemistry molecules	3D mental rotation
Chemistry	General chemistry	3D mental rotation and field independence
Physics	Pulley systems	3D mental rotation and mental folding
Astronomy	Planetary orbits	Mental folding
Geology	Structure of a mountain area	3D mental rotation, mental folding, dual tasks of working memory
Meteorology	El Niño phenomenon	Mental folding

The usual finding is that visuospatial processing is less influential in the advanced stages of science proficiency (see Uttal and Cohen 2012; see also Langlois et al. 2015; Stieff et al. 2018). In other words, the expertise acquired later in training is more relevant than visuospatial processing to thrive in the science fields. This means that when students do not have the necessary scientific knowledge, they rely more on visuospatial abilities to succeed in their disciplines. Later, they reach a point in which science expertise is more influential. In the next subsections, we provide examples of the importance of visuospatial processing in novice university students of diverse science areas (see summary in Table 3.2).

3.1.1 Anatomy and Medicine

Several correlational studies have investigated the effects of different visuospatial abilities on academic achievement in anatomy. An example of the ability of mental rotation in three-dimensions (3D) is provided by Garg et al. (2001), who investigated 146 university participants (50% females) studying the bones of the human hand through a computer visualization model. Findings showed that the scores in a 3D mental rotation instruments (the Mental Rotations Test) were significant predictors of success in the hand bones examination. Similarly, Lufler et al. (2012) used the Mental Rotations Test on 352 first-year medicine undergraduates. Students in the top 25% of Mental Rotations Test scores surpassed those in the bottom 25%, in both practical and written examinations of a gross anatomy course. Last, Loftus et al. (2017) also employed the scores of the Mental Rotations Test, in this case, to perform a median split of their sample of 29 adult participants (35% females). Students with higher 3D mental rotation outperformed their lower-scoring counterparts in solving thorax and ankle anatomy tests that involved mental rotations, cross-sections, and intersecting planes.

In addition to 3D mental rotation and anatomy, other visuospatial abilities have been influential to learn other health science topics. For example, Fiorella and Mayer (2017) reported two studies with a total of 202 undergraduates (64% females) learning about the respiratory system from text-only passages. Combining the scores of a 3D mental rotation test and a mental folding instrument, the authors calculated a composite score of spatial ability. This measure of spatial ability was a significant predictor of learning about the respiratory system, as measured in retention, transfer, and drawing of facts and concepts. Mayer and Sims (1994, Experiment 2) used a two-dimensional (2D) test of mental rotation and a test of mental folding in a study with 97 university participants. With the data of both instruments, an aggregated spatial ability score was calculated. The participants studied a multimedia presentation of the respiratory system, where a short animation and concurrent narration explained processes such as inhaling and exhaling. Results revealed that high spatial ability students outperformed low spatial participants. Also, in two experiments totaling 68 psychology undergraduates, Wiegmann et al. (1992) observed small to medium correlations (values from $r = .24$ to $r = .32$) between scores on a field independence test (the Group Embedded Figures Test) and scores on learning tests about the autonomic nervous system.

3.1.2 Surgery

Mental rotation in 3D has also been related to surgery tasks. For example, Wanzel et al. (2002) observed significant correlations in 37 surgical residents between the Mental Rotations Test and complex surgical skills. Keehner et al. (2006) investigated 44 non-medicine university students training laparoscopic surgical skills through a virtual reality system. Results revealed that, for both the beginning and ending training sessions, 3D mental rotation scores were correlated with performance in these laparoscopic tasks. Similarly, Risucci et al. (2001) investigated 94 surgeons participating in a basic laparoscopic skills course. Findings showed that 3D mental rotation and field independence were correlated to speed for doing the surgery drills.

Also concerning field independence is the study by Gibbons et al. (1986), where 58 general surgery residents showed large correlations ($r = .55$ and $r = .60$) between technical surgical skills and scores in the Hidden Figures Test, a field independence measure. Keehner et al. (2004) investigated the relationship between surgical and mental folding abilities of 93 surgeons (10% females). Results showed a significant correlation between these abilities ($r = .39$), but only for the novice surgeons. More experienced professionals did not show this relationship ($r = .02$), echoing that visuospatial processing is most important in the novice stages of scientific competence.

3.1.3 Biology

Mental rotation and other visuospatial abilities have also been influential in learning biology contents. For example, Bartholomé and Bromme (2009) described a correlational study of 84 university participants (77% females) learning botany from multimedia modules. Spatial ability was measured by combining mental rotation and field independence scores. This aggregated spatial ability score was significantly correlated with different multimedia learning achievements, including the classification of parts of plants ($r = .42$, $p < .01$) and of whole plants ($r = .45$, $p < .01$). In Seufert et al. (2009, Experiment 2), 78 education and psychology university participants (74% females) studied multimedia material about the structure and function of the enzyme ATP-Synthase. Mental rotation in 2D was measured with half of the Card Rotations Test, and mental folding was assessed with half of the Paper Folding Test. The mean of both tests scores was used as their aggregated spatial ability score. Results in the comprehension and transfer tests showed that the composite spatial ability was a significant predictor for learning.

In an experimental approach, Lord (1990) employed three spatial ability tests with the Ekstrom et al. (1976) battery to measure 250 university students in a biology class. Students in the lowest third of these spatial abilities were allocated to control and treatment groups for the rest of the year. The training involved weekly spatial tasks requiring imagining slices of 3D objects that led to 2D shapes. At the end of the class, the students were assessed in a written final exam with items about the interpretation of charts, graphs, and diagrams, and a final laboratory exam involving macroscopic and microscopic biology. Results revealed that participants in the spatial training group outperformed those in the control group in these biological tasks.

3.1.4 Chemistry

In two experiments with university students, Barrett and Hegarty (2016) assessed the role of 3D mental rotation in the manipulation of virtual organic chemistry molecules. In Experiment 1, 125 students (51% females) aligned 3D molecules to 2D diagrams, whereas in Experiment 2, 142 participants (51% females) aligned two 3D models. In both experiments, individuals with higher scores in the Mental Rotations Tests outperformed students scoring low mental rotations in these virtual chemistry tasks. Similarly, Stull and Hegarty (2016) reported two experiments with undergraduate chemistry participants attempting translations of chemical representations, where 3D mental rotation was measured using an online Mental Rotations Test. Both Experiment 1 (105 students, 54% females) and Experiment 2 (104 students, 65% females) showed that 3D mental rotation was a significant predictor of task achievement, although this spatial ability effect was reduced when the tasks were executed using manipulative models (see also Castro-Alonso et al. this volume-c, Chap. 7).

Carter et al. (1987) used two different visuospatial tests in science and engineering undergraduates: (a) the Purdue Visualization of Rotations, a 3D mental rotation test; and (b) the Find A Shape Puzzle, a field independence test. With the data from both measures, the authors divided the sample in three (high, medium, and low spatial ability students) and compared the performance of these groups in multiple-choice chemistry exams. Globally, high spatial ability students outperformed low spatial students in the written exams, which covered different chemistry topics (e.g., molecular geometry, atomic structure, gas laws, and stoichiometry). Pribyl and Bodner (1987) employed the same two tests to measure 3D mental rotation and field independence in university students of four organic chemistry courses. The authors combined the two tests scores, and then compared chemistry exam performance between "low spatial students" (who scored ≤0.5 standard deviations from the mean) and "high spatial students" (scoring ≥0.5 standard deviations from the mean). High spatial students outperformed low spatial students. This spatial ability effect was observed in exam items that required the mental manipulation of 2D molecules and to solve other general chemistry problems, but was not present when the questions could be answered by rote memory.

3.1.5 Physics and Astronomy

For physics topics, we highlight research employing the Paper Folding Test, a measure of mental folding. For example, in three experiments with university students, Hegarty and Sims (1994) investigated the effects of 3D mental rotation (the Mental Rotations Test) and mental folding (the Paper Folding Test) on *mental animation* performance (inference of movements) from static images of pulley systems. Results showed that high visuospatial processing students outperformed the lower visuospatial achievers in these mechanical tasks. Similar findings were reported by Schweppe et al. (2015) in two experiments with a total of 253 undergraduates (75% females), where a computer shortened version of the Paper Folding Test was used. Findings revealed that the scores in mental folding were positively correlated with retention and comprehension of the structure and functioning of pulley systems shown in multimedia presentations.

Kozhevnikov et al. (2007, Study 3) investigated 15 university students solving kinematics problems about the motion of objects shown in graphs. Using the results of the first half of the Paper Folding Test, students were classified as low or high in mental folding. Students who scored highly on the mental folding test could solve motion graph tasks better than students who scored poorly on the folding test. As the eye-tracking analysis showed, this difference was partially explained by the fact that students who scored well on the mental folding test could better integrate the information in both graphical axes.

Kühl et al. (2018) found similar results in astronomy, in an experiment with 198 university students (76% females) asked to learn about planets orbiting the sun.

When the topic was shown as a static depiction, students with higher results on the Paper Folding Test outperformed the lower visuospatial processing peers (see also Castro-Alonso et al. this volume-b, Chap. 5).

3.1.6 Geology and Meteorology

Piburn et al. (2005) investigated 103 geology university participants (53% females) studying topographic maps. Mental folding (measured with an adapted Surface Development Test) was a significant predictor of learning, but 3D mental rotation (modified Cubes Rotation Test) was not. Hambrick et al. (2012) studied the performance of 67 adult participants (46% females) in inferring the structure of a mountainous area. Participants took six tests of visuospatial processing (including 3D mental rotation, mental folding, and dual tasks of working memory), from which a composite score was calculated. For geology novices, visuospatial processing was a significant predictor of performance in the task. However, in yet another example of the scientific expertise factor, the effect of visuospatial processing was not significant among geology experts and advanced students.

The common Paper Folding Test has also been employed in research about meteorology topics. Jaeger et al. (2016) reported two experiments with university participants studying text-only passages describing the Pacific Ocean weather phenomenon of *El Niño*. Experiment 1 investigated 72 participants (62% females) and used the whole Paper Folding Test, whereas Experiment 2 investigated 72 students (66% females) and used half of the test. Both experiments showed that the mental folding scores predicted comprehension, employing different learning measures. Last, in an experiment with 84 adults (69% females) studying booklets about the formation of lightning, Eitel et al. (2019) compared seductive to non-seductive designs (see also Castro-Alonso et al. this volume-b, Chap. 5). Mental folding scores were significantly correlated with performance scores of recall ($r = .26$, $p = .02$) and transfer ($r = .42$, $p < .001$). In other words, mental folding ability supported the learning of this meteorology topic, independent of the booklet design.

In short, studies with different visuospatial processing tests and diverse fields of health and natural sciences show that visuospatial abilities are key assets to thrive in science education and practice. Although much of the evidence is correlational, there are also some experimental findings that have shown these beneficial effects of visuospatial processing on science learning and achievement.

3.2 Science Education Influencing Visuospatial Processing

As noted above, the relation between science education and visuospatial processing is reciprocal. Thus far we have considered how visuospatial processing supports learning about health and natural sciences. Now we consider the other side of the

Table 3.3 Examples of visuospatial abilities that have been enhanced by different science learning experiences

Science area	Visuospatial ability	Learning experience
Anatomy	3D mental rotation	Gross anatomy
Anatomy	3D mental rotation	Virtual anatomy
Dentistry	Cross sections on 3D shapes	Dental expertise
Biology	2D mental rotation and mental folding	Biology classes
Biology	Field independence	Microbiology
Veterinary	3D mental rotation	Canine anatomy
Chemistry	3D mental rotation	Chemistry expertise
Physics	Mental rotation, mental folding, field independence	Physics classes and labs
Geology	3D mental rotation	Geology expertise

relation: How does learning about health and natural sciences influence different visuospatial abilities.

Although this side of the relation has received less attention, there are several examples of correlations between enrollment in health and natural sciences and performance on visuospatial processing. For example, Peters et al. (1995) compared scores on the Mental Rotations Test between 312 students (43% females) in science areas (engineering, biology, and physics) and 324 students (69% females) in arts, social sciences, and humanities. The science students outperformed the participants from the other areas in the visuospatial task. Employing a larger sample of university students ($N > 2000$), Peters et al. (2006) reported significantly higher scores on the Mental Rotations Test in science students than in social science participants.

These studies are only correlational, and thus the direction of causality cannot be assessed. However, there is also experimental evidence that indicates that learning health or natural science can improve visuospatial reasoning (see Table 3.3).

As Table 3.3 shows, generally, these studies have been conducted on a single science discipline. For example, a recent meta-analysis by Langlois et al. (2019) showed that anatomy education provided an effective training for visuospatial processing, notably mental rotation. The following subsections describe additional experimental evidence for different science disciplines.

3.2.1 *Anatomy and Dentistry*

The study by Lufler et al. (2012), described in Sect. 3.1.1, measured the performance of 255 first-year medical students on the Mental Rotations Test. The study compared 3D mental rotation scores before and after a one-semester gross anatomy course. The class required dissections of cadavers and the study of 2D anatomical pictures from textbooks. The mental rotation scores of students of both genders increased significantly by the end of the semester.

Similarly, Vorstenbosch et al. (2013) reported findings with first-year university students of medicine (experimental group, $n = 242$, 67% females) and first-year students of education (control group, $n = 258$, 95% females) attempting the Mental Rotations Test. The treatment given to the students of medicine consisted of 160 h (4 weeks) of study of the gross anatomy of the thorax, abdomen, and pelvis. Instruction utilized visualizations and cross-sections. For the control group of education students, a course lasting 4 weeks presented topics of social science research methods. Medical students learning from the anatomy materials improved more on the Mental Rotations Test than the education participants learning about research methods. The treatment showed an effect size of $d = 0.12$. According to the benchmarks by Cohen (1988), this value represents a small-sized effect.

Recently, Guimarães et al. (2019) investigated 611 medicine university students (65% females) training with three different regimes of virtual anatomy: cardiovascular, musculoskeletal, and cardiovascular plus musculoskeletal. Scores in the Mental Rotations Test were higher after all the types of anatomy training, compared to the scores before the treatments. The effect size was large ($d = 1.57$) for the three training regimes. However, as the authors acknowledged, the study included the limitation of not including a control group. Hence, these results should be interpreted with caution (see also Sect. 3.3.4, below).

Hegarty et al. (2009) investigated the spatial skills of novice and more advanced dentistry students. Two of the spatial tests were novel and involved performing mental horizontal or vertical cross sections on 3D objects, a skill useful for professional dentists. The only significant difference between the two groups of different expertise was observed in the test of cross sections from 3D teeth. There were no differences in cross sections from abstract 3D objects or in the more general mental rotation tests. These findings suggest that dentistry training facilitates the development of specific visuospatial skills relevant to the profession but does not help performance in more general visuospatial tasks. In other words, this training did not produce transfer to related tasks (see below, Sect. 3.3).

3.2.2 Biology and Veterinary Medicine

For biology education, we describe two examples, involving correlational and quasi-experimental designs. The correlational evidence is provided by Macnab and Johnstone (1990), who measured spatial skills in participants of different ages, ranging from primary school children to the postgraduate levels. Three different visuospatial skills were measured, which in order of difficulty were: (a) the ability to use different 2D sections to mentally construct a 3D object; (b) mental rotations with 2D figures; and (c) the ability to imagine a 2D slice taken from a cut surface of a 3D object. Results showed that these visuospatial skills tended to be higher in the students who had taken biology classes, compared to participants lacking this area of studies.

Concerning the quasi-experiment, Lennon (2000) investigated 59 microbiology undergraduates performing a 20 min weekly training of visuospatial activities with clay bacteria models. After this regime of 10 weeks, the experimental group improved on a field independence instrument (the Hidden Figures Test), but not on the other two spatial abilities measured, namely 3D mental rotation (Cube Comparisons Test) and mental folding (Paper Folding Test).

In the related field of veterinary medicine, Provo et al. (2002) investigated 128 undergraduates (75% females) learning a canine anatomy course. The course was effective in improving scores in a test of mental rotation with 3D figures. The authors suggested that this improvement was to be expected, as the learning activities involved visualizing cross sections and images of the 3D anatomy of the dog.

Similar results were observed in a study by Gutierrez et al. (2017) with 81 veterinary medicine undergraduates (86% females). The students completed 32 weeks of an integrated veterinary anatomy curriculum, which entailed an average of 57 h of anatomy laboratories. Results showed that this course was effective to improve the scores in the Mental Rotations Test.

3.2.3 Chemistry, Physics, and Geology

Concerning chemistry knowledge, we provide an example of correlational evidence. In two studies with 88 and 96 undergraduates (50% females in each), Hausmann (2014) investigated science (chemistry and engineering) and non-science students (philosophy and English). Science students outperformed non-science participants on the Mental Rotation Test. The effects favoring chemistry and engineering areas were large, both in Experiment 1 ($\eta_P^2 = .28$) and Experiment 2 ($\eta_P^2 = .39$).

Burnett and Lane (1980) investigated the effects of taking four academic semesters of physics on the mental rotation of 142 university students. The participants in the fields of humanities and social sciences improved less in mental rotation ability than did those in the physics and mathematics programs. Likewise, Pallrand and Seeber (1984) showed that 10 weeks of university physics classes and laboratories could enhance the visuospatial abilities of mental rotation, mental folding, and field independence.

Lastly, there is also correlational evidence that studying geology can affect visuospatial processing. Resnick and Shipley (2013) investigated 37 doctorate professionals from three different fields, namely geology (47% females), organic chemistry (18% females), and English (50% females). Both geologists and chemists performed significantly better than the English experts on the Mental Rotations Test. However, there were no subject-area differences in the test of field independence (Hidden Figures Test) and the dual visuospatial task of working memory (Symmetry Span Task).

Concluding this section, both the correlational and the stricter experimental evidence support the relation between being more knowledgeable or learning in different science areas and scoring high in different visuospatial processing tests.

3.3 Visuospatial Training

In a recent meta-analysis of 42 effect sizes in twin studies, King et al. (2019) reported that visuospatial processing was largely heritable. However, the study also showed that environmental factors played a role, although smaller than the genetic variables. In other words, although visuospatial processing is inherited as a fixed feature, it is also dependent on the environment, and, thus, it can be trained.

Due to the relation between visuospatial processing and science academic achievement, researchers are looking for ways to train visuospatial abilities, to enhance science learning and performance (e.g., Cheng 2017; Stieff and Uttal 2015; Uttal et al. 2013). Since visuospatial processing develops through childhood, there is substantial time available for children's instructors to include activities inside and outside the classroom to foster visuospatial processing, and eventually boost science achievement (see Newcombe and Frick 2010).

However, the link between training in visuospatial activities and increasing science performance scores is not always straightforward. In fact, this link involves two assumptions (see Stieff and Uttal 2015): (a) visuospatial processing can be *trained* (see also Baenninger and Newcombe 1989), and thus practicing a visuospatial task allows improvement in that specific task and in very similar ones; and (b) visuospatial processing can also be *transferred*, and thus practicing a visuospatial task allows that its improvement does also affect an untrained scientific task. The second assumption has been much harder to prove (Stieff and Uttal 2015; see also Barnett and Ceci 2002).

In a similar demarcation, Wright et al. (2008) distinguish between *instance-based* and *process-based* spatial training. The instance-based perspective predicts that training specific visuospatial processes will develop only similar processes. In contrast, process-based training predicts a more general impact, where training can develop similar and relatively different processes, so, transfer to new visuospatial and science tasks could occur.

Considering these classifications and the literature on working memory and spatial training (e.g., Könen et al. 2016; Melby-Lervåg et al. 2016; Uttal and Cohen 2012), we describe three categories to order visuospatial training, as follows:

1. *near transfer*: includes mostly training, instance-based, practice, or retest effects. For example, training in one visuospatial process (e.g., 2D mental rotation) transfers to that same process or a similar process but with minor differences (e.g., the same type of 2D mental rotation with new shapes; see Fig. 3.2a);
2. *intermediate transfer*: includes more transfer and certain process-based effects. For example, training in one visuospatial process (e.g., 2D mental rotation) transfers to a similar process with some differences (e.g., 3D mental rotation or mental folding; see Fig. 3.2b); and
3. *far transfer*: includes an even larger degree of transfer and process-based effects. For example, training in one visuospatial process (e.g., 2D mental rotation) transfers to a different process with more differences (e.g., visuospatial working memory tasks or science topics; see Fig. 3.2c).

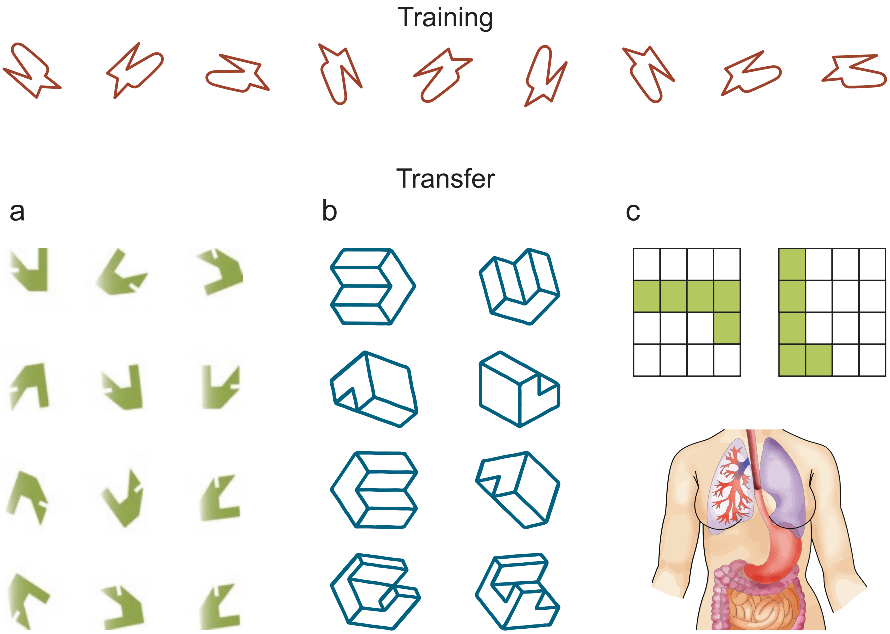


Fig. 3.2 Three degrees of transfer effects. The example shows 2D mental rotation training showing effects categorized as (**a**) near, (**b**) intermediate, and (**c**) far transfer

3.3.1 Near Transfer Effects

Uttal et al. (2013) conducted a meta-analysis of 206 studies and 1,038 effect sizes, in order to investigate training in spatial abilities. The overall effect size favoring this near transfer was medium-sized ($g = 0.47$), supporting the claim that spatial ability can be improved with practice.

Individual studies have also shown these near transfer effects. For example, concerning 3D mental rotation, Meneghetti et al. (2017) investigated 72 female university students training 35 min weekly (for 5 weeks) on this visuospatial ability. Accuracy and speed of the mental rotations improved after the training sessions. Roach et al. (2019) selected 33 science university students (73% females) who scored poorly on the pen-and-paper Mental Rotations Test. The participants trained with an electronic version of this test and improved their performance.

Also, both studies promoted other techniques to improve these training effects. Meneghetti et al. (2017) showed that giving the students an additional rotation strategy led to better training results. Roach et al. (2019) reported a method in which the participants observed the positions at which experts had looked while solving the mental rotations. This signaling by experts was more effective than only training with the instrument.

Hoyek et al. (2009) investigated 16 physical education students (38% females) receiving 240 min (12 sessions of 20 min each) of mental rotation training. The training involved mental rotations with familiar and abstract 3D and 2D figures. A near transfer was revealed when the training produced a significantly higher performance on the Mental Rotation Test, a 3D instrument that had not been practiced.

Kail (1986) reported an effective training of 2D mental rotations with alphanumeric characters. Eight adults (50% females) participated in 16 sessions of 240 trials each, totaling 3,840 training trials. At the end of the sessions, participants were 25% faster than before the treatment. Likewise, Goldstein and Chance (1965) reported that 26 undergraduates (50% females) improved their scores on the Embedded Figures Test of field independence after eight blocks of trials.

Spatial working memory can also be trained. Li et al. (2008) investigated the effects of 15-min training for 45 days of two Spatial 2-Back Tasks. For both immediate and delayed (3 months later) testing, participants demonstrated near transfer to other n-back working memory tasks, but not larger transfer effects to dual tasks of working memory. Similarly, in a study with psychology undergraduates, Chooi and Thompson (2012) observed that daily training (30 min, 4 days a week) in n-back tasks showed near transfer, but not intermediate transfer to another working memory task (the dual task known as the Operation Span Task), nor far transfer to mental rotation or other functions of visuospatial memory.

Also, Redick et al. (2013) and Colom et al. (2013) reported that visuospatial and auditory stimuli in n-back tasks were effective for training but not for transfer. Redick and colleagues did not find an intermediate transfer to two dual tasks of working memory (the Symmetry Span Task and the Running Letter Span), nor a far transfer to 15 separate measures of verbal and nonverbal tasks (assessing multitasking, fluid and crystallized intelligence, and perceptual speed). Colom et al. did not observe an intermediate transfer to three dual tasks of working memory, nor far transfer to the fluid intelligence factor.

Similarly, other studies (e.g., Owen et al. 2010; von Bastian and Eschen 2016) have shown near transfer effects for visuospatial working memory tasks but have failed to show more transfer to other cognitive and academic tests.

3.3.2 Intermediate Transfer Effects

There is evidence that mental rotation training can lead to intermediate transfer. Sometimes this transfer is observed in a change of dimensionality between the mental rotation tasks. For example, Moreau (2012) investigated 46 university students (52% females) receiving videogame training with Tetris-type blocks, in both 3D and 2D versions. Task performance was measured with mental rotation tests that varied both in stimulus type (human body or polygon) and in dimensionality (3D or 2D). Training with the 2D block videogame led to near transfer, that is, better performance in mental rotations of 2D polygons and 2D bodies. However, training with the 3D videogame produced an intermediate transfer, leading to better mental rotations of 3D polygons, 3D bodies, 2D polygons, and 2D bodies.

Other forms of spatial training have also shown intermediate transfer. For example, Stericker and LeVesconte (1982) trained 45 introductory psychology students (53% females) on three different tests, which measured 3D mental rotation, mental folding, and field independence, respectively. There were six weekly training sessions, each one lasting approximately 20 min per test. Training led to improvement on the three tests as well as on an untrained 2D mental rotation instrument.

Similarly, Lord (1985) divided a sample of 84 undergraduate biology students into experimental and control conditions. The treatment for the experimental group included weekly training with abstract spatial tasks that required imagining 2D surfaces taken from bisections of 3D objects. At post-test, the experimental group, but not the control group, showed an intermediate transfer to a mental rotation test and a mental folding test.

As with spatial abilities, visuospatial working memory tasks can also show intermediate transfer effects to other working memory tests. Although the meta-analysis of 145 experiments (87 studies) by Melby-Lervåg et al. (2016) revealed a lack of intermediate and far transfer for general working memory tasks, the effects were more encouraging when the tests involved visuospatial stimuli. In fact, for visuospatial working memory training, the meta-analysis showed small to medium intermediate effects, both for immediate measures ($g = 0.28$) and delayed post-tests after months ($g = 0.40$).

The n-back paradigm has been also employed to investigate intermediate transfer of visuospatial working memory tasks. For example, Soveri et al. (2017) conducted a meta-analysis of training on different formats of this task. This analysis of 41 experiments ($N = 2{,}105$ participants) showed a medium effect size ($g = 0.59$), in which training in one format of the N-Back Task showed a near transfer to similar formats. Although there was intermediate transfer to different visuospatial working memory tasks, it was small ($g = 0.18$).

Analogously, Minear et al. (2016) trained 31 university students (74% females) on the Spatial N-Back Task for a total of 20 sessions (20 min each). The training showed a medium to large near transfer effect ($\eta_P^2 = 0.09$). It also showed large intermediate transfer effects to the Object N-Back Task ($\eta_P^2 = 0.40$), and two dual tasks of working memory, namely the Symmetry Span ($\eta_P^2 = 0.20$) and the Rotation Span ($\eta_P^2 = 0.15$).

An example of visual working memory producing intermediate transfer is provided in Adam and Vogel (2018). They investigated 101 adult participants (69% females) training in a visual working memory task with colored squares. The six training sessions (1 h each) showed training effects on the working memory task, and intermediate transfer to a different task that used the same colored stimuli. However, there was no evidence of far transfer to other visual tasks or a fluid intelligence measure.

3.3.3 Far Transfer Effects

The challenge of transferring knowledge or abilities from one area to another less similar area has interested researchers for a long time (e.g., Thorndike and Woodworth 1901). However, many current studies and reviews, mostly with working memory training paradigms (e.g., Gathercole et al. 2019; Sala and Gobet 2017; Simons et al. 2016), show that far transfer is rarely obtained.

Similarly, the evidence that visuospatial training can lead to far transfer is scarcer than that supporting near and intermediate transfer (see Gathercole et al. 2019; Simons et al. 2016; Stieff and Uttal 2015). An experiment by Lord (1990) with university students (see Sect. 3.1.3) provides an example of effective far transfer. He reported that weekly training with tasks of imagining 2D surfaces taken from 3D objects improved performance in a biology course.

Stephenson and Halpern (2013) reported a study with university students training 5 days a week for 4 weeks (for approximately 20 min each day). Visuospatial working memory training showed intermediate transfer that led to higher scores on the Paper Folding Test of mental folding. They also demonstrated some far transfer, with two of four tests of fluid intelligence improving as a result of the visuospatial memory training.

Also, Sanchez (2012) compared 60 university students (38% females) randomly allocated to two different videogame training groups, namely, a visuospatial first-person shooter or a verbal word-making condition (see also Castro-Alonso and Fiorella this volume, Chap. 6). The visuospatial training group outperformed the verbal condition on the task of writing an essay about volcanic eruptions. In other words, for this geology task, visuospatial training was more effective than verbal training.

A summary of these near, intermediate, and transfer effects of visuospatial training is provided in Table 3.4.

3.3.4 Methodological Shortcomings in Training Studies

Although we showed evidence of transfer from visuospatial training, these effects were usually in the near or intermediate degrees. In other words, the literature shows infrequent far transfer that reaches the academic fields of health and natural sciences.

In addition, many studies that show the transfer of visuospatial abilities and working memory training to academic outcomes, have methodological shortcomings, as summarized n Table 3.5.

A recurring issue reported by different researchers (e.g., Könen et al. 2016; Melby-Lervåg and Hulme 2013; Redick et al. 2015; Shipstead et al. 2012; Simons et al. 2016; von Bastian and Oberauer 2014) is the quality of the control groups employed. In addition, as shown in the meta-analysis by Langlois et al. (2019),

Table 3.4 Examples of visuospatial training regimes showing near (N), intermediate (I), and far (F) degrees of transfer

Visuospatial training	Did transfer to	Did not transfer to	References
3D mental rotation	3D mental rotation (N)		Meneghetti et al. (2017) and Roach et al. (2019)
3D and 2D mental rotation	Novel 3D mental rotation (N)		Hoyek et al. (2009)
2D mental rotation	2D mental rotation (N)		Kail (1986)
Spatial 2-Back Tasks	Novel n-back tasks (N)	Dual tasks of working memory (I)	Li et al. (2008)
N-back tasks	Novel n-back tasks (N)	Dual tasks of working memory (I), mental rotation (F), visuospatial memory (F)	Chooi and Thompson (2012)
Visuospatial n-back tasks	Novel visuospatial n-back tasks (N)	Dual tasks of working memory (I), fluid intelligence (F)	Colom et al. (2013) and Redick et al. (2013)
2D block mental rotation videogame	Novel 2D mental rotations (N)	Novel 3D mental rotations (I)	Moreau (2012)
3D block mental rotation videogame	Novel 3D (N) and novel 2D (I) mental rotations		Moreau (2012)
3D mental rotation, mental folding, field independence	Novel 2D mental rotation (I)		Stericker and LeVesconte (1982)
Imagining 2D surfaces from 3D objects	Mental rotation (I), mental folding (I)		Lord (1985)
N-back task	Novel n-back tasks (N), visuospatial working memory tasks (I)		Soveri et al. (2017)
Spatial N-Back Task	Spatial N-Back Task (N), Object N-Back Task (I), dual tasks of working memory (I)		Minear et al. (2016)
Visual working memory	Visual working memory and similar tasks (N, I)	Novel visual tasks (F), fluid intelligence (F)	Adam and Vogel (2018)
Imagining 2D surfaces from 3D objects	Biology course (F)		Lord (1990)
Visuospatial working memory	Mental folding (I), fluid intelligence (F)	Fluid intelligence (F)	Stephenson and Halpern (2013)
First-person shooter videogame	Volcanic eruption essay (F)		Sanchez (2012)

Table 3.5 Problematic methodologic approaches and suggested solutions in research of visuospatial and working memory training

Problem	Suggested solution
No control group	Incorporate a control condition
Passive control group	Use an active control group
Non-random assignment to conditions	Randomly assign participants to every condition
Not measuring a pretest baseline	Assess all conditions at pretest
Small sample sizes	Use at least 20 participants per condition
Far transfer without intermediate transfer	Pilot the instruments to measure far and intermediate transfer
Immediate testing only	Include also delayed testing (e.g., after a month)
A single far transfer measure	Use multiple far transfer measures

studies sometimes do not include any control group. Of course, studies without proper controls cannot unambiguously demonstrate training effects, as the improvement could be due to many different confounds (cf. about confounding variables for multimedia design in Castro-Alonso et al. 2016).

As agreed by many authors (e.g., Melby-Lervåg and Hulme 2013; Redick et al. 2015; Simons et al. 2016), the gold standard for a control group is an *active control*, which performs cognitive and engaging activities like the treatment group. In contrast, a *passive control* performs non-equivalent actions and sometimes no activity at all. The problem of using passive controls is that they are usually much less engaged than active controls, so they could artificially inflate the treatment effect.

Consider the following example with an n-back training paradigm. The meta-analysis of 20 studies by Au et al. (2015) reported a small but significant effect ($g = 0.24$) of n-back training on far transfer to fluid intelligence. However, a Bayesian reanalysis by Dougherty et al. (2016), which considered the effects of passive versus active controls separately, revealed that the far transfer was only present with passive controls. In other words, the studies that used a design including active controls did not show the far transfer effects of n-back training.

In addition to the control group problem, two other issues, regarded as *severe* by Simons et al. (2016), are: (a) failing to assign the participants randomly to the treatment and control conditions, and (b) failing to assess all conditions at pretest (see also discussion in Melby-Lervåg and Hulme 2013; Redick et al. 2015). These problems can produce effects that might be attributed to the visuospatial treatment when in fact they could correspond to individual differences between the treatment and control groups.

A less problematic issue, regarded as *substantial* by Simons et al. (2016), is the small number of participants in the experimental and control conditions. Redick et al. (2015) recommend 20 participants per compared groups as the absolute minimum for reliable statistical power.

Another problem mentioned by researchers (e.g., Melby-Lervåg and Hulme 2013; Redick et al. 2015) is that visuospatial training that shows far transfer (e.g., to academic measures) should also show intermediate transfer (e.g., to working memory tests). By showing these two degrees of transfer simultaneously, it would be safer to conclude that the training improved academic performance because the relevant variable (e.g., visuospatial working memory) was also enhanced.

Finally, Redick et al. (2015) also made two suggestions for future research on visuospatial training. The first is to include delayed testing after months of training, to see if the transfer effects that are recorded in immediate testing are durable. The second is to use multiple measures of far or intermediate transfer, rather than one instrument only.

3.4 Discussion

Science phenomena are usually represented and communicated using visual and spatial information. Thus, visuospatial processing is a crucial aspect of understanding and communicating topics of health and natural sciences. In this chapter we provided evidence of a two-way relationship between visuospatial processing and science education. One side of the coin shows that visuospatial processing helps learning about science topics. The other side shows that education in science can enhance different visuospatial abilities.

The examples we provided included diverse visuospatial abilities (e.g., 3D mental rotation, 2D mental rotation, mental folding, spatial working memory, and dual tasks of working memory), measured by different instruments (e.g., the Mental Rotations Test and the Paper Folding Test), and related to diverse scientific disciplines (e.g., medicine, anatomy, surgery, dentistry, biology, chemistry, physics, and geology).

We also described visuospatial training as a potentially positive method to increase visuospatial abilities, and ideally induce far transfer that could lead to increases in science academic results. Still, there are several problematic implementations in the research literature about visuospatial training, and we suggested some potential solutions to avoid them in the future.

3.4.1 Instructional Implications for Health and Natural Sciences

A first instructional implication, general in scope, is to showcase visuospatial processing for science education. As commented by Wai and Kell (2017), formal education is currently oriented to developing language and math skills, in detriment of visuospatial abilities. Thus, the implication is to produce awareness of the importance of visuospatial processing for health and natural sciences.

A second implication, derived from the first, is what Newcombe (2016) described as *spatializing the science curriculum*. Teachers, lecturers, and instructional designers should include visuospatial processing activities in the classes of health and natural sciences. Examples suggested by Wai and Kell (2017) are: (a) laboratory and manipulative activities, for example in medicine, anatomy, and biology; (b) exploring chemical phenomena with models of 3D molecules; and (c) reasoning with 2D figures and shapes, for example, in physics.

A third implication, derived from the two first, is that the visuospatial exercises should be varied, and not limited, for example, to mental rotations. The activities should be broad enough to include all the abilities that are dependent on visuospatial processing (e.g., Castro-Alonso and Atit this volume, Chap. 2) and that will be useful for syllabi in the sciences. For example, Levine et al. (2016) suggested using spatial language, deciphering spatial relationships, scaling visualizations, and understanding symbolic representations (e.g., maps and graphs).

A fourth implication is related to the influence that teachers and instructors can have on their students (e.g., Rosenthal and Jacobson 1968), and in particular how they can be scientific role models (cf. Miller et al. 2015; Rochon et al. 2016). As such, it is essential that these professionals show proficiency in visuospatial activities when presenting topics and problems in health and natural sciences. The problem is that some teachers may lack visuospatial abilities (see Atit et al. 2018), and thus remedial actions are suggested for these cases.

3.4.2 Future Research Directions

An important addition to the findings that visuospatial processing is necessary for education and performance in sciences, is to determine which visuospatial ability is needed most for a specific task or topic in health and natural sciences. This research gap has been noted in surgical training (Anastakis et al. 2000), dentistry (Hegarty et al. 2009), chemistry and biochemistry (Oliver-Hoyo and Babilonia-Rosa 2017; Wu and Shah 2004), and in other science fields (see Castro-Alonso et al. 2019a).

Another possible research direction is to investigate moderating variables that affect visuospatial processing and science education, including: (a) the design of the educational resources (see Castro-Alonso et al. this volume-b, Chap. 5; see also Castro-Alonso et al. 2018b); (b) the sex or gender of the participants (see Castro-Alonso and Jansen this volume, Chap. 4; see also Castro-Alonso et al. 2019b); and (c) possible gender-science stereotypes (e.g., Miller et al. 2018).

Also, future research could investigate boundary conditions in the relation between interactive science multimedia and visuospatial processing (see Castro-Alonso and Fiorella this volume, Chap. 6; see also Wu and Shah 2004) or between embodied science activities and visuospatial processing (see Castro-Alonso et al. this volume-c, Chap. 7; see also Castro-Alonso et al. 2015).

The last research direction we suggest is based on the indication by Newcombe and Frick (2010) that visuospatial activities can be incorporated into the classroom and also be fostered outside the classroom, such as at home, or during play or sports.

We suggest future investigations of the effects of visuospatial activities beyond the science classroom, to informal contexts, such as museums and outdoor activities.

3.4.3 Conclusion

Visuospatial processing is key to learning and succeeding in the disciplines of health and natural sciences. There is a reciprocal relation between visuospatial processing and science learning: (a) visuospatial processing helps learning about science, and (b) training and education in science enhances visuospatial abilities. Therefore, visuospatial training can be a potentially effective way to enhance visuospatial abilities and support better outcomes in fields of health and natural sciences. Nevertheless, far transfer from visuospatial training to science achievement is not easy to achieve.

Acknowledgments Support from PIA-CONICYT Basal Funds for Centers of Excellence Project FB0003 is gratefully acknowledged. The first author is thankful to Mariana Poblete for her assistance, and to Ignacio Jarabran for helping with the illustrations.

References

Adam, K. C. S., & Vogel, E. K. (2018). Improvements to visual working memory performance with practice and feedback. *PLoS One, 13*(8), e0203279. https://doi.org/10.1371/journal.pone.0203279.

Anastakis, D. J., Hamstra, S. J., & Matsumoto, E. D. (2000). Visual-spatial abilities in surgical training. *The American Journal of Surgery, 179*(6), 469–471. https://doi.org/10.1016/S0002-9610(00)00397-4.

Atit, K., Miller, D. I., Newcombe, N. S., & Uttal, D. H. (2018). Teachers' spatial skills across disciplines and education levels: Exploring nationally representative data. *Archives of Scientific Psychology, 6*(1), 130–137. https://doi.org/10.1037/arc0000041.

Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., & Jaeggi, S. M. (2015). Improving fluid intelligence with training on working memory: A meta-analysis. *Psychonomic Bulletin & Review, 22*(2), 366–377. https://doi.org/10.3758/s13423-014-0699-x.

Baenninger, M., & Newcombe, N. S. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles, 20*(5–6), 327–344. https://doi.org/10.1007/BF00287729.

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn?: A taxonomy for far transfer. *Psychological Bulletin, 128*(4), 612–637. https://doi.org/10.1037/0033-2909.128.4.612.

Barrett, T. J., & Hegarty, M. (2016). Effects of interface and spatial ability on manipulation of virtual models in a STEM domain. *Computers in Human Behavior, 65*, 220–231. https://doi.org/10.1016/j.chb.2016.06.026.

Bartholomé, T., & Bromme, R. (2009). Coherence formation when learning from text and pictures: What kind of support for whom? *Journal of Educational Psychology, 101*(2), 282–293. https://doi.org/10.1037/a0014312.

Burnett, S. A., & Lane, D. M. (1980). Effects of academic instruction on spatial visualization. *Intelligence, 4*(3), 233–242. https://doi.org/10.1016/0160-2896(80)90021-5.

Carter, C. S., Larussa, M. A., & Bodner, G. M. (1987). A study of two measures of spatial ability as predictors of success in different levels of general chemistry. *Journal of Research in Science Teaching, 24*(7), 645–657. https://doi.org/10.1002/tea.3660240705.

Castro-Alonso, J. C., & Atit, K. (this volume). Different abilities controlled by visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 23–51). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_2.

Castro-Alonso, J. C., & Fiorella, L. (this volume). Interactive science multimedia and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 145–173). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_6.

Castro-Alonso, J. C., & Jansen, P. (this volume). Sex differences in visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 81–110). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_4.

Castro-Alonso, J. C., & Uttal, D. H. (2019). Spatial ability for university biology education. In S. Nazir, A.-M. Teperi, & A. Polak-Sopińska (Eds.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2018 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 283–291). Cham: Springer. https://doi.org/10.1007/978-3-319-93882-0_28.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015). The potential of embodied cognition to improve STEAM instructional dynamic visualizations. In X. Ge, D. Ifenthaler, & J. M. Spector (Eds.), *Emerging technologies for STEAM education: Full STEAM ahead* (pp. 113–136). New York: Springer. https://doi.org/10.1007/978-3-319-02573-5_7.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2016). Comparing apples and oranges? A critical look at research on learning from statics versus animations. *Computers & Education, 102*, 234–243. https://doi.org/10.1016/j.compedu.2016.09.004.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018a). Computerized and adaptable tests to measure visuospatial abilities in STEM students. In T. Andre (Ed.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2017 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 337–349). Cham: Springer. https://doi.org/10.1007/978-3-319-60018-5_33.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2018b). Learning symbols from permanent and transient visual presentations: Don't overplay the hand. *Computers & Education, 116*, 1–13. https://doi.org/10.1016/j.compedu.2017.08.011.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2019a). Visuospatial tests and multimedia learning: The importance of employing relevant instruments. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (pp. 89–99). New York: Routledge. https://doi.org/10.4324/9780429283895-8.

Castro-Alonso, J. C., Wong, M., Adesope, O. O., Ayres, P., & Paas, F. (2019b). Gender imbalance in instructional dynamic versus static visualizations: A meta-analysis. *Educational Psychology Review*, *31*(2), 361–387. https://doi.org/10.1007/s10648-019-09469-1.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (this volume-a). VAR: A battery of computer-based instruments to measure visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 207–229). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_8.

Castro-Alonso, J. C., Ayres, P., & Sweller, J. (this volume-b). Instructional visualizations, cognitive load theory, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 111–143). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_5.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (this volume-c). Embodied cognition, science education, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 175–205). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_7.

Cheng, Y.-L. (2017). The improvement of spatial ability and its relation to spatial training. In M. S. Khine (Ed.), *Visual-spatial ability in STEM education: Transforming research into practice* (pp. 143–172). Cham: Springer. https://doi.org/10.1007/978-3-319-44385-0_8.

Chooi, W.-T., & Thompson, L. A. (2012). Working memory training does not improve intelligence in healthy young adults. *Intelligence, 40*(6), 531–542. https://doi.org/10.1016/j.intell.2012.07.004.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale: Erlbaum.

Colom, R., Román, F. J., Abad, F. J., Shih, P. C., Privado, J., Froufe, M., et al. (2013). Adaptive n-back training does not improve fluid intelligence at the construct level: Gains on individual tests suggest that training may enhance visuospatial processing. *Intelligence, 41*(5), 712–727. https://doi.org/10.1016/j.intell.2013.09.002.

Dougherty, M. R., Hamovitz, T., & Tidwell, J. W. (2016). Reevaluating the effectiveness of n-back training on transfer through the Bayesian lens: Support for the null. *Psychonomic Bulletin & Review, 23*(1), 306–316. https://doi.org/10.3758/s13423-015-0865-9.

Eitel, A., Bender, L., & Renkl, A. (2019). Are seductive details seductive only when you think they are relevant? An experimental test of the moderating role of perceived relevance. *Applied Cognitive Psychology, 33*(1), 20–30. https://doi.org/10.1002/acp.3479.

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Kit of factor-referenced cognitive tests*. Princeton: Educational Testing Service.

Fiorella, L., & Mayer, R. E. (2017). Spontaneous spatial strategy use in learning from scientific text. *Contemporary Educational Psychology, 49*, 66–79. https://doi.org/10.1016/j.cedpsych.2017.01.002.

Garg, A. X., Norman, G., & Sperotable, L. (2001). How medical students learn spatial anatomy. *The Lancet, 357*(9253), 363–364. https://doi.org/10.1016/S0140-6736(00)03649-7.

Gathercole, S. E., Dunning, D. L., Holmes, J., & Norris, D. (2019). Working memory training involves learning new skills. *Journal of Memory and Language, 105*, 19–42. https://doi.org/10.1016/j.jml.2018.10.003.

Gibbons, R. D., Baker, R. J., & Skinner, D. B. (1986). Field articulation testing: A predictor of technical skills in surgical residents. *Journal of Surgical Research, 41*(1), 53–57. https://doi.org/10.1016/0022-4804(86)90008-9.

Goldstein, A. G., & Chance, J. E. (1965). Effects of practice on sex-related differences in performance on Embedded Figures. *Psychonomic Science, 3*(1–12), 361–362. https://doi.org/10.3758/bf03343180.

Guimarães, B., Firmino-Machado, J., Tsisar, S., Viana, B., Pinto-Sousa, M., Vieira-Marques, P., et al. (2019). The role of anatomy computer-assisted learning on spatial abilities of medical students. *Anatomical Sciences Education, 12*(2), 138–153. https://doi.org/10.1002/ase.1795.

Gutierrez, J. C., Chigerwe, M., Ilkiw, J. E., Youngblood, P., Holladay, S. D., & Srivastava, S. (2017). Spatial and visual reasoning: Do these abilities improve in first-year veterinary medical students exposed to an integrated curriculum? *Journal of Veterinary Medical Education, 44*(4), 669–675. https://doi.org/10.3138/jvme.0915-158R3.

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., & Gernsbacher, M. A. (2007). The science of sex differences in science and mathematics. *Psychological Science in the Public Interest, 8*(1), 1–51. https://doi.org/10.1111/j.1529-1006.2007.00032.x.

Hambrick, D. Z., Libarkin, J. C., Petcovic, H. L., Baker, K. M., Elkins, J., Callahan, C. N., et al. (2012). A test of the circumvention-of-limits hypothesis in scientific problem solving: The case of geological bedrock mapping. *Journal of Experimental Psychology: General, 141*(3), 397–403. https://doi.org/10.1037/a0025927.

Hausmann, M. (2014). Arts versus science—Academic background implicitly activates gender stereotypes on cognitive abilities with threat raising men's (but lowering women's) performance. *Intelligence, 46*, 235–245. https://doi.org/10.1016/j.intell.2014.07.004.

Hegarty, M., & Sims, V. K. (1994). Individual differences in mental animation during mechanical reasoning. *Memory & Cognition, 22*(4), 411–430. https://doi.org/10.3758/bf03200867.

Hegarty, M., Keehner, M., Khooshabeh, P., & Montello, D. R. (2009). How spatial abilities enhance, and are enhanced by, dental education. *Learning and Individual Differences, 19*(1), 61–70. https://doi.org/10.1016/j.lindif.2008.04.006.

Hoyek, N., Collet, C., Rastello, O., Fargier, P., Thiriet, P., & Guillot, A. (2009). Enhancement of mental rotation abilities and its effect on anatomy learning. *Teaching and Learning in Medicine, 21*(3), 201–206. https://doi.org/10.1080/10401330903014178.

Jaeger, A. J., Taylor, A. R., & Wiley, J. (2016). When, and for whom, analogies help: The role of spatial skills and interleaved presentation. *Journal of Educational Psychology, 108*(8), 1121–1139. https://doi.org/10.1037/edu0000121.

Kail, R. (1986). The impact of extended practice on rate of mental rotation. *Journal of Experimental Child Psychology, 42*(3), 378–391. https://doi.org/10.1016/0022-0965(86)90032-9.

Keehner, M., Tendick, F., Meng, M. V., Anwar, H. P., Hegarty, M., Stoller, M. L., et al. (2004). Spatial ability, experience, and skill in laparoscopic surgery. *The American Journal of Surgery, 188*(1), 71–75. https://doi.org/10.1016/j.amjsurg.2003.12.059.

Keehner, M., Lippa, Y., Montello, D. R., Tendick, F., & Hegarty, M. (2006). Learning a spatial skill for surgery: How the contributions of abilities change with practice. *Applied Cognitive Psychology, 20*(4), 487–503. https://doi.org/10.1002/acp.1198.

Khine, M. S. (Ed.). (2017). *Visual-spatial ability in STEM education*. Cham: Springer. https://doi.org/10.1007/978-3-319-44385-0.

King, M. J., Katz, D. P., Thompson, L. A., & Macnamara, B. N. (2019). Genetic and environmental influences on spatial reasoning: A meta-analysis of twin studies. *Intelligence, 73*, 65–77. https://doi.org/10.1016/j.intell.2019.01.001.

Könen, T., Strobach, T., & Karbach, J. (2016). Working memory. In T. Strobach & J. Karbach (Eds.), *Cognitive training: An overview of features and applications* (pp. 59–68). Cham: Springer. https://doi.org/10.1007/978-3-319-42662-4_6.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science, 31*(4), 549–579. https://doi.org/10.1080/15326900701399897.

Kühl, T., Stebner, F., Navratil, S. C., Fehringer, B. C. O. F., & Münzer, S. (2018). Text information and spatial abilities in learning with different visualizations formats. *Journal of Educational Psychology, 110*(4), 561–577. https://doi.org/10.1037/edu0000226.

Langlois, J., Bellemare, C., Toulouse, J., & Wells, G. A. (2015). Spatial abilities and technical skills performance in health care: A systematic review. *Medical Education, 49*(11), 1065–1085. https://doi.org/10.1111/medu.12786.

Langlois, J., Bellemare, C., Toulouse, J., & Wells, G. A. (2019). Spatial abilities training in anatomy education: A systematic review. *Anatomical Sciences Education*. Advance online publication. https://doi.org/10.1002/ase.1873.

Lennon, P. A. (2000). Improving students' flexibility of closure while presenting biology content. *The American Biology Teacher, 62*(3), 177–180. https://doi.org/10.2307/4450869.

Levine, S. C., Foley, A., Lourenco, S., Ehrlich, S., & Ratliff, K. (2016). Sex differences in spatial cognition: Advancing the conversation. *Wiley Interdisciplinary Reviews: Cognitive Science, 7*(2), 127–155. https://doi.org/10.1002/wcs.1380.

Li, S.-C., Schmiedek, F., Huxhold, O., Röcke, C., Smith, J., & Lindenberger, U. (2008). Working memory plasticity in old age: Practice gain, transfer, and maintenance. *Psychology and Aging, 23*(4), 731–742. https://doi.org/10.1037/a0014343.

Loftus, J. J., Jacobsen, M., & Wilson, T. D. (2017). Learning and assessment with images: A view of cognitive load through the lens of cerebral blood flow. *British Journal of Educational Technology, 48*(4), 1030–1046. https://doi.org/10.1111/bjet.12474.

Lord, T. R. (1985). Enhancing the visuo-spatial aptitude of students. *Journal of Research in Science Teaching, 22*(5), 395–405. https://doi.org/10.1002/tea.3660220503.

Lord, T. R. (1990). Enhancing learning in the life sciences through spatial perception. *Innovative Higher Education, 15*(1), 5–16. https://doi.org/10.1007/BF00889733.

Lufler, R. S., Zumwalt, A. C., Romney, C. A., & Hoagland, T. M. (2012). Effect of visual–spatial ability on medical students' performance in a gross anatomy course. *Anatomical Sciences Education, 5*(1), 3–9. https://doi.org/10.1002/ase.264.

Macnab, W., & Johnstone, A. H. (1990). Spatial skills which contribute to competence in the biological sciences. *Journal of Biological Education, 24*(1), 37–41. https://doi.org/10.1080/00219266.1990.9655099.

Mathewson, J. H. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. *Science Education, 83*(1), 33–54. https://doi.org/10.1002/(SICI)1098-237X(199901)83:1<33::AID-SCE2>3.0.CO;2-Z.

Mathewson, J. H. (2005). The visual core of science: Definition and applications to education. *International Journal of Science Education, 27*(5), 529–548. https://doi.org/10.1080/09500690500060417.

Mayer, R. E., & Sims, V. K. (1994). For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. *Journal of Educational Psychology, 86*(3), 389–401. https://doi.org/10.1037/0022-0663.86.3.389.

Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology, 49*(2), 270–291. https://doi.org/10.1037/a0028228.

Melby-Lervåg, M., Redick, T. S., & Hulme, C. (2016). Working memory training does not improve performance on measures of intelligence or other measures of “far transfer”: Evidence from a meta-analytic review. *Perspectives on Psychological Science, 11*(4), 512–534. https://doi.org/10.1177/1745691616635612.

Meneghetti, C., Cardillo, R., Mammarella, I. C., Caviola, S., & Borella, E. (2017). The role of practice and strategy in mental rotation training: Transfer and maintenance effects. *Psychological Research, 81*(2), 415–431. https://doi.org/10.1007/s00426-016-0749-2.

Miller, D. I., Eagly, A. H., & Linn, M. C. (2015). Women’s representation in science predicts national gender-science stereotypes: Evidence from 66 nations. *Journal of Educational Psychology, 107*(3), 631–644. https://doi.org/10.1037/edu0000005.

Miller, D. I., Nolla, K. M., Eagly, A. H., & Uttal, D. H. (2018). The development of children’s gender-science stereotypes: A meta-analysis of 5 decades of U.S. Draw-A-Scientist studies. *Child Development, 89*(6), 1943–1955. https://doi.org/10.1111/cdev.13039.

Minear, M., Brasher, F., Guerrero, C. B., Brasher, M., Moore, A., & Sukeena, J. (2016). A simultaneous examination of two forms of working memory training: Evidence for near transfer only. *Memory & Cognition, 44*(7), 1014–1037. https://doi.org/10.3758/s13421-016-0616-9.

Moreau, D. (2012). Differentiating two- from three-dimensional mental rotation training effects. *The Quarterly Journal of Experimental Psychology, 66*(7), 1399–1413. https://doi.org/10.1080/17470218.2012.744761.

Newcombe, N. S. (2016). Thinking spatially in the science classroom. *Current Opinion in Behavioral Sciences, 10*, 1–6. https://doi.org/10.1016/j.cobeha.2016.04.010.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education, 4*(3), 102–111. https://doi.org/10.1111/j.1751-228X.2010.01089.x.

Oliver-Hoyo, M., & Babilonia-Rosa, M. A. (2017). Promotion of spatial skills in chemistry and biochemistry education at the college level. *Journal of Chemical Education, 94*(8), 996–1006. https://doi.org/10.1021/acs.jchemed.7b00094.

Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., et al. (2010). Putting brain training to the test. *Nature, 465*(7299), 775–778. https://doi.org/10.1038/nature09042.

Pallrand, G. J., & Seeber, F. (1984). Spatial ability and achievement in introductory physics. *Journal of Research in Science Teaching, 21*(5), 507–516. https://doi.org/10.1002/tea.3660210508.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*(1), 39–58. https://doi.org/10.1006/brcg.1995.1032.

Peters, M., Lehmann, W., Takahira, S., Takeuchi, Y., & Jordan, K. (2006). Mental Rotation Test performance in four cross-cultural samples (N = 3367): Overall sex differences and the role of academic program in performance. *Cortex, 42*(7), 1005–1014. https://doi.org/10.1016/s0010-9452(08)70206-5.

Piburn, M. D., Reynolds, S. J., McAuliffe, C., Leedy, D. E., Birk, J. P., & Johnson, J. K. (2005). The role of visualization in learning from computer-based images. *International Journal of Science Education, 27*(5), 513–527. https://doi.org/10.1080/09500690412331314478.

Pribyl, J. R., & Bodner, G. M. (1987). Spatial ability and its role in organic chemistry: A study of four organic courses. *Journal of Research in Science Teaching, 24*(3), 229–240. https://doi.org/10.1002/tea.3660240304.

Provo, J., Lamar, C., & Newby, T. (2002). Using a cross section to train veterinary students to visualize anatomical structures in three dimensions. *Journal of Research in Science Teaching, 39*(1), 10–34. https://doi.org/10.1002/tea.10007.

Redick, T. S., Shipstead, Z., Harrison, T. L., Hicks, K. L., Fried, D. E., Hambrick, D. Z., et al. (2013). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology: General, 142*(2), 359–379. https://doi.org/10.1037/a0029082.

Redick, T. S., Shipstead, Z., Wiemers, E. A., Melby-Lervåg, M., & Hulme, C. (2015). What's working in working memory training? An educational perspective. *Educational Psychology Review, 27*(4), 617–633. https://doi.org/10.1007/s10648-015-9314-6.

Resnick, I., & Shipley, T. F. (2013). Breaking new ground in the mind: An initial study of mental brittle transformation and mental rigid rotation in science experts. *Cognitive Processing, 14*(2), 143–152. https://doi.org/10.1007/s10339-013-0548-2.

Risucci, D., Geiss, A., Gellman, L., Pinard, B., & Rosser, J. (2001). Surgeon-specific factors in the acquisition of laparoscopic surgical skills. *The American Journal of Surgery, 181*(4), 289–293. https://doi.org/10.1016/S0002-9610(01)00574-8.

Roach, V. A., Fraser, G. M., Kryklywy, J. H., Mitchell, D. G. V., & Wilson, T. D. (2019). Guiding low spatial ability individuals through visual cueing: The dual importance of where and when to look. *Anatomical Sciences Education, 12*(1), 32–42. https://doi.org/10.1002/ase.1783.

Rochon, P. A., Davidoff, F., & Levinson, W. (2016). Women in academic medicine leadership: Has anything changed in 25 years? *Academic Medicine, 91*(8), 1053–1056. https://doi.org/10.1097/acm.0000000000001281.

Rosenthal, R., & Jacobson, L. (1968). Pygmalion in the classroom. *The Urban Review, 3*(1), 16–20. https://doi.org/10.1007/bf02322211.

Sala, G., & Gobet, F. (2017). Does far transfer exist? Negative evidence from chess, music, and working memory training. *Current Directions in Psychological Science, 26*(6), 515–520. https://doi.org/10.1177/0963721417712760.

Sanchez, C. A. (2012). Enhancing visuospatial performance through video game training to increase learning in visuospatial science domains. *Psychonomic Bulletin & Review, 19*(1), 58–65. https://doi.org/10.3758/s13423-011-0177-7.

Schweppe, J., Eitel, A., & Rummer, R. (2015). The multimedia effect and its stability over time. *Learning and Instruction, 38*, 24–33. https://doi.org/10.1016/j.learninstruc.2015.03.001.

Seufert, T., Schütze, M., & Brünken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude-treatment-interaction study. *Learning and Instruction, 19*(1), 28–42. https://doi.org/10.1016/j.learninstruc.2008.01.002.

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin, 138*(4), 628–654. https://doi.org/10.1037/a0027473.

Simons, D. J., Boot, W. R., Charness, N., Gathercole, S. E., Chabris, C. F., Hambrick, D. Z., et al. (2016). Do "brain-training" programs work? *Psychological Science in the Public Interest, 17*(3), 103–186. https://doi.org/10.1177/1529100616661983.

Soveri, A., Antfolk, J., Karlsson, L., Salo, B., & Laine, M. (2017). Working memory training revisited: A multi-level meta-analysis of n-back training studies. *Psychonomic Bulletin & Review, 24*(4), 1077–1096. https://doi.org/10.3758/s13423-016-1217-0.

Stephenson, C. L., & Halpern, D. F. (2013). Improved matrix reasoning is limited to training on tasks with a visuospatial component. *Intelligence, 41*(5), 341–357. https://doi.org/10.1016/j.intell.2013.05.006.

Stericker, A., & LeVesconte, S. (1982). Effect of brief training on sex-related differences in visual–spatial skill. *Journal of Personality and Social Psychology, 43*(5), 1018–1029. https://doi.org/10.1037/0022-3514.43.5.1018.

Stieff, M., & Uttal, D. H. (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review, 27*(4), 607–615. https://doi.org/10.1007/s10648-015-9304-8.

Stieff, M., Origenes, A., DeSutter, D., Lira, M., Banevicius, L., Tabang, D., et al. (2018). Operational constraints on the mental rotation of STEM representations. *Journal of Educational Psychology, 110*(8), 1160–1174. https://doi.org/10.1037/edu0000258.

Stull, A. T., & Hegarty, M. (2016). Model manipulation and learning: Fostering representational competence with virtual and concrete models. *Journal of Educational Psychology, 108*(4), 509–527. https://doi.org/10.1037/edu0000077.

Thorndike, E. L., & Woodworth, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions (I). *Psychological Review, 8*(3), 247–261.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how? In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 57, pp. 147–181). San Diego: Academic. https://doi.org/10.1016/B978-0-12-394293-7.00004-2.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., et al. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352–402. https://doi.org/10.1037/a0028446.

von Bastian, C. C., & Eschen, A. (2016). Does working memory training have to be adaptive? *Psychological Research, 80*(2), 181–194. https://doi.org/10.1007/s00426-015-0655-z.

von Bastian, C. C., & Oberauer, K. (2014). Effects and mechanisms of working memory training: A review. *Psychological Research, 78*(6), 803–820. https://doi.org/10.1007/s00426-013-0524-6.

Vorstenbosch, M. A. T. M., Klaassen, T. P. F. M., Donders, A. R. T., Kooloos, J. G. M., Bolhuis, S. M., & Laan, R. F. J. M. (2013). Learning anatomy enhances spatial ability. *Anatomical Sciences Education, 6*(4), 257–262. https://doi.org/10.1002/ase.1346.

Wai, J., & Kell, H. J. (2017). What innovations have we already lost?: The importance of identifying and developing spatial talent. In M. S. Khine (Ed.), *Visual-spatial ability in STEM education: Transforming research into practice* (pp. 109–124). Cham: Springer. https://doi.org/10.1007/978-3-319-44385-0_6.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817–835. https://doi.org/10.1037/a0016127.

Wanzel, K. R., Hamstra, S. J., Anastakis, D. J., Matsumoto, E. D., & Cusimano, M. D. (2002). Effect of visual-spatial ability on learning of spatially-complex surgical skills. *The Lancet, 359*(9302), 230–231. https://doi.org/10.1016/S0140-6736(02)07441-X.

Wiegmann, D. A., Dansereau, D. F., McCagg, E. C., Rewey, K. L., & Pitre, U. (1992). Effects of knowledge map characteristics on information processing. *Contemporary Educational Psychology, 17*(2), 136–155. https://doi.org/10.1016/0361-476X(92)90055-4.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review, 15*(4), 763–771. https://doi.org/10.3758/PBR.15.4.763.

Wu, H.-K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*(3), 465–492. https://doi.org/10.1002/sce.10126.

Chapter 4
Sex Differences in Visuospatial Processing

Juan C. Castro-Alonso and Petra Jansen

Approaching the first quarter of the twenty-first century, men and women exhibit only minor differences that could affect their academic performance. These similar educational outcomes are also observed in the university disciplines of health and natural sciences. For example, reviewing different meta-analyses, Hyde (2014) found an overall support for the *gender similarities hypothesis*. In other words, most of the variables analyzed (e.g., verbal performance, mathematics skills, self-esteem, academic self-concept, and leadership effectiveness) showed small to negligible differences between the sexes.

In contrast, few exceptions showing moderate to large sex differences were found (e.g., mental rotation in three-dimensions, sensation seeking, and physical aggression). Similarly, the comprehensive metasynthesis of 106 meta-analyses (over 12 million participants and 21,000 effects), by Zell et al. (2015), showed that the overall effect size of the difference between males and females in psychological traits was of $d = 0.21$, which represents a small size effect according to Cohen (1988). These meta-analyses support that university men and women tend to show similar academic abilities, including those needed to learn about health and natural sciences.

Nevertheless, as in Hyde (2014), the study by Zell et al. (2015) signaled a number of psychological traits that showed moderate to large gender or sex differences (e.g., mental rotation, aggression, and peer attachment). In this chapter, we consider one of those variables that challenged the gender similarities hypothesis, namely, mental rotation. We also include several related visuospatial processing tasks, as they are all involved in health and natural sciences achievement (see Castro-Alonso and Uttal this volume, Chap. 3).

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

P. Jansen
Faculty of Psychology, Education, and Sport Science, University of Regensburg,
Regensburg, Germany

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_4

Although these visuospatial tasks tend to show less marked sex differences than mental rotation instruments, they still show sex variations favoring men. This applies for both the *spatial ability* and the *working memory* tasks, jointly considered *small-scale visuospatial processing abilities* (see Castro-Alonso and Atit this volume, Chap. 2), where men usually outperform women.

For example, Stericker and LeVesconte (1982) showed that, among the introductory psychology students assessed, men outperformed women in all four spatial ability tests, including mental rotation with three-dimensional (3D) images, mental rotation with two-dimensional (2D) shapes, mental folding, and field independence. Also, in the meta-analysis of spatial and visual working memory tasks by Voyer et al. (2017), there was a small overall effect ($d = 0.16$) indicating the better performance of men compared to women in these tests.

Similarly, the study by Geiger and Litwiller (2005) with 63 university students (76% females) showed males performing better than females in a dual visuospatial task of working memory. Only the visual working memory test known as *Object Location Memory* shows women tending to outscore men (e.g., Eals and Silverman 1994).

The main goal of this chapter is to describe the existence of sex differences in the abilities described above as well as to provide examples to diminish them. The specific aims of this review are the following: (a) describe diverse degrees of sex differences, related to the different visuospatial abilities investigated; (b) provide sociocultural (nurture) and biological (nature) explanations for these sex differences; (c) show that visuospatial training could potentially help to diminish this gap; (d) discuss instructional implications for health and natural sciences; and (e) offer future research directions for the investigation of these sex differences in visuospatial processing.

4.1 Sex Differences in Different Visuospatial Processing Abilities

There are two research traditions concerning instruments to measure visuospatial processing abilities (see Hegarty et al. 2006). Firstly, we describe the abilities that belong to the literature about *spatial ability*, including mental rotation, mental folding, and field independence. Secondly, we address the abilities to solve *visuospatial working memory* tasks, including spatial working memory, visual working memory, and dual visuospatial tasks of working memory. These tasks are described in Castro-Alonso and Atit (this volume, Chap. 2). A summary of the expected directions and degrees of sex differences is provided in Table 4.1.

Table 4.1 Expected directions and degrees of sex differences for various visuospatial processing abilities

Research tradition	Visuospatial ability	Direction	Degree
Spatial ability	3D mental rotation	Men	MMM
	2D mental rotation	Men	MM
	Mental folding	Men	M
	Field independence	Men	M
Working memory	Spatial working memory	Men	M
	Visual working memory (Square patterns)	Men	M
	Visual working memory (Position of objects)	Women	W
	Dual visuospatial working memory	Men	M

The abbreviatures indicate the direction and the magnitude or degree. For example, MMM favors men over women to a greater extent than MM, which also surpasses M

4.1.1 Mental Rotation

Mental rotation was defined by Ekstrom et al. (1976) as the ability to perceive a whole figure and rotating it in mind. The spatial ability literature consistently shows that men have higher scores than women in common mental rotation instruments. The meta-analysis by Voyer et al. (1995) revealed an overall effect size of $d = 0.56$, and the meta-analysis by Linn and Petersen (1985) showed an average of $d = 0.73$. These values represent medium to large effect sizes favorable to males. These aggregated results have also been shown with specific mental rotation tests, which can be classified as 3D vs. 2D instruments. Following this distinction, the favorable outcomes for men tend to be larger with 3D as compared to 2D mental rotation tests (cf. Voyer and Jansen 2016).

Figure 4.1a shows an item from the *Mental Rotations Test*, a 3D mental rotation instrument, whereas Fig.4.1b depicts three questions from the *Card Rotations Test*, a 2D instrument (see also Castro-Alonso and Atit this volume, Chap. 2; Castro-Alonso et al. this volume-a, Chap. 8). Regarding the 3D mental rotation test in the figure, for every item, the participants must indicate which two figures from the given four on the right side are rotated versions of the shape on the left side. For the items of the 2D mental rotation test, the correct answer is to indicate which pictures are the same (S) as the given shape on the left side, only rotated versions, and which are different (D), meaning that they are rotated and mirror-reversed.

The Mental Rotations Test has shown a male advantage in different populations, including: (a) medicine and anatomy students (Guillot et al. 2007; Vorstenbosch et al. 2013), (b) dentistry learners (Hegarty et al. 2009), (c) psychology students (Levinson et al. 2007; Terlecki and Newcombe 2005; Terlecki et al. 2008), (d) psychology and chemistry undergraduates (Hegarty 2018), (e) university students from various disciplines (Cherney 2008; Reilly et al. 2016), (f) undergraduates practicing sports and physical education (Jansen et al. 2016; Moreau et al. 2012), and (g) adults in general (Hegarty et al. 2006; Loftus et al. 2017).

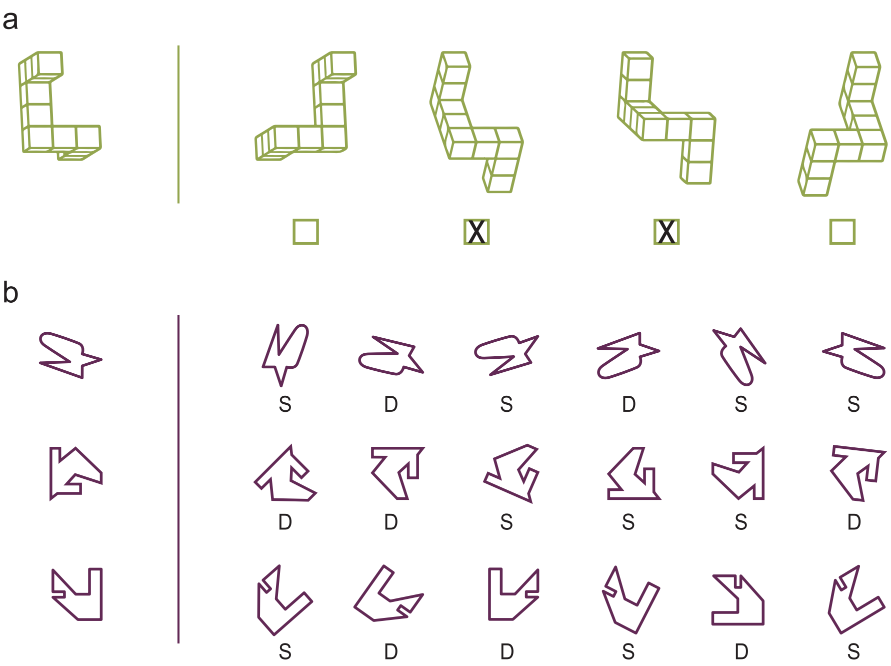


Fig. 4.1 Examples of items of mental rotation instruments, requesting (**a**) 3D mental rotation, and (**b**) 2D mental rotation. The correct answer in each case is given. Note that these are not actual items, but adaptations

Furthermore, in a large study ($N > 240{,}000$, 48% females) with data from 40 countries and seven self-identified ethnic groups attempting a short version of the Mental Rotations Test, Silverman et al. (2007) reported that the differences favoring males were observed in all countries and ethnicities, and the overall effect represented a medium size. In addition, Masters and Sanders (1993) conducted a meta-analysis of 14 studies of adults completing the Mental Rotations Test ($N = 5{,}144$; 58% females). In all of the 14 studies men outscored women, and the overall mean effect size was large ($d = 0.90$).

Another 3D mental rotation test that shows these sex differences is the *Purdue Visualization of Rotations*. For example, in a meta-analysis of 40 studies (70 effect sizes), Maeda and Yoon (2013) observed that there was an overall medium effect size of $g = 0.57$ for men outperforming women. The meta-analysis also showed that the sex advantage for men was larger ($g = 0.67$) when a time limit was applied to the test. Not included in this meta-analysis, Bodner and Guay (1997) reported four studies with different chemistry students ($N = 1{,}928$). In all of these studies, men consistently outperformed women. More recently, Ferguson et al. (2015), investigating undergraduates (Study 3) and adults (Study 4), showed similar findings in a revised computer version of the test.

These sex effects have also been observed for 2D mental rotation instruments (but see Castro-Alonso et al. 2018b). For example, in an experiment with 95 introductory psychology undergraduates (72% females), Mayer and Massa

(2003) reported that males outperformed females on the Card Rotations Test. Campos et al. (2004) investigated 129 university graduates of different ages (53% females) completing a mental rotation test with 2D shapes. Results showed an overall medium size effect ($d = 0.49$) for all ages, and a large effect ($d = 0.84$) for the youngest group of participants (< 41 years), always favorable to men.

When 3D and 2D mental rotation instruments are compared on a given study, usually the results favoring men are higher for the 3D tests. Three examples are provided in: (a) the study by Sanders et al. (1982) with 1,031 psychology undergraduates (65% females); (b) the report by Peters et al. (1995) with 101 participants (47% females); and (c) the study by Cherney (2008) with 61 university students (51% females). In these cases, men showed noticeably higher scores than women on the 3D test (the Mental Rotations Test), but not such large differences on the 2D test (the Card Rotations Test). Similar findings were reported by Roberts and Bell (2003) with 32 right-handed psychology undergraduates (50% females), and by Reilly et al. (2016) with 309 university students (66% females). In both studies, males outperformed females on the 3D instrument (the Mental Rotations Test) but not on the other tasks involving 2D mental rotations.

4.1.2 Mental Folding and Field Independence

As described by Ekstrom et al. (1976), *mental folding* (also called spatial visualization) requires mental rotation but also additional processing that involves serial operations and mental restructuring. Although mental folding can show sex differences, the effects are generally smaller than for mental rotation. For example, the meta-analyses by Linn and Petersen (1985) and by Voyer et al. (1995) reported small overall effect sizes favoring males over females ($d = 0.13$ and $d = 0.19$, respectively), which are smaller than the medium to large effect sizes reported for mental rotation (see Sect. 4.1.1).

The most common instrument for measuring mental folding is the *Paper Folding Test*. Sanchez and Wiley (2010) conducted a study with 96 psychology undergraduates (50% females), where the Paper Folding Test showed sex differences favoring men. Several reports have also shown favorable outcomes for men, but usually smaller in size when compared to mental rotation. For example, in an experiment by Peters et al. (1995), men outperformed women on the Mental Rotations Test (3D mental rotation), but not the Card Rotations Tests (2D mental rotation) nor the Paper Folding Test (mental folding). Also, the study with psychology undergraduates by Mayer and Massa (2003) showed that the sex differences favorable to men were larger in the Card Rotations Test than in the Paper Folding Test. Similarly, Stephenson and Halpern (2013) reported that 136 university students (52% females) presented larger sex effects for men on the Mental Rotation Test than on the Paper Folding Test. Lastly, Lord (1987) investigated 250 undergraduates (50% females) from both science and nonscience disciplines, and observed that the difference favoring males over females was about four times larger on a 3D mental rotation instrument (the Cube Comparisons Test) than on the Paper Folding Test.

Sex differences have also been investigated in other mental folding tests. For example, in a study by Nordvik and Amponsah (1998) with university students from fields of technology (N = 161, 42% females) and social science (N = 293, 77% females), participants were assessed on the *Surface Development Test*. In addition, the students were also measured in a 3D mental rotation instrument (Mental Rotations Test) and a 2D mental rotation test (Spatial Relations). Although men outperformed women on the three tests, the effects were the largest in the 3D mental rotation test (d = 0.85 for technology students and d = 1.06 for social science participants), followed by the 2D rotation instrument (d = 0.48 for technology and d = 0.41 for social science), and being smallest for the Surface Development Test of mental folding (d = 0.39: technology; d = 0.33: social science).

The last spatial ability presented here, *field independence*, requires perceiving a shape independently of its context (Witkin 1949). This ability can also show sex effects favoring men. For example, Guillot et al. (2007) investigated 184 students (29% females) attempting the field independence instrument known as the *Group Embedded Figures Test*. It was observed that males outperformed females in this test of spatial ability. Nevertheless, field independence, as mental folding, does not exhibit the large sex differences of mental rotation. On a sample of 221 adult participants (62% females), Hegarty et al. (2006) reported that the sex effects favoring men on the Mental Rotations Test were not observed for the Group Embedded Figures Test. Similarly, in the study by Reilly et al. (2016) with university students, men outperformed women only in the 3D mental rotation test, but not in the instruments measuring 2D mental rotation or the Group Embedded Figures Test. Analogously, the study by Lord (1987), which showed difference favoring men for a 3D mental rotation instrument (the Cube Comparisons Test) and a mental folding test (the Paper Folding Test), failed to show these sex effects on the field independence instrument called the *Hidden Figures Test*.

4.1.3 Spatial Working Memory

Spatial working memory is usually measured by tests that show visuospatial elements sequentially (cf. Darling et al. 2006). Voyer et al. (2017) conducted a meta-analysis of different spatial working memory tests, which included 48 samples and 69 effect sizes. It considered the *Corsi Block Tapping Test* and similar instruments involving location and sequencing. The meta-analysis revealed that men outperformed women with a small effect size (d = 0.18).

One study of this meta-analysis, conducted by Ruggiero et al. (2008), can be used to illustrate the sex differences in this Corsi test. In Experiment 2, 64 adult participants (50% females) attempted the traditional wooden version of the test and also a 2D mental rotations instrument. Results showed that both tasks presented sex differences favoring men, but they were smaller in the Corsi test than in the task of mental rotation. Thus, the trend with spatial abilities is also observed in spatial working memory tests, as they show smaller sex differences than mental rotation tasks.

In another study, Piccardi et al. (2008) investigated two different sizes of the Corsi test, with a sample of 75 undergraduate students (47% females). In the original version, an investigator tapped specific sequences of nine wooden block, and the students had to replicate these sequences. In the walking, large-size version, there were nine squares placed on the floor, which were stepped on in sequences, and the students had to walk and step on, following the series. It was observed that in both original and walk-size versions, men outperformed women.

In contrast, there are studies which could not indicate sex effects on the Corsi Block Tapping Test (e.g., Castro-Alonso et al. 2018b). For example, Kessels et al. (2000) investigated 140 adults (44% females), including 70 healthy participants and 70 patients with cerebral lesions, attempting the original test with nine wooden blocks. Although there was a slight tendency of men to remember more blocks than women (0.27 blocks), this difference was not significant. In the study by Woods et al. (2016), 189 adults (42% females) attempted a computerized test that involved clicking on ten 2D squared (as opposed to tapping on nine 3D wooden blocks in the traditional Corsi test). In this modern adaptation of the Corsi instrument, there were no significant sex differences in any of the metrics, including accuracy and reaction times.

There are other spatial working memory instruments, besides the Corsi test. For example, those following the *n-back task* paradigm. Voyer et al. (2017) performed a meta-analysis with eight samples and 19 effect sizes. Again, it was observed that men outperformed women with a small effect size (d = 0.20). A study from the meta-analysis that provides greater detail of these sex effects is the experiment with 36 psychology undergraduates (50% females) by Lejbak et al. (2011). They employed 2-back tasks of three different versions: verbal, object, and spatial tasks. When the sexes were compared, women were surpassed in the object and spatial versions, but there were no sex differences in the verbal format.

4.1.4 Visual Working Memory

Visual working memory is typically measured by instruments that show visuospatial elements simultaneously (cf. Darling et al. 2006). For visual working memory tests requiring memory for patterns, Voyer et al. (2017) performed a meta-analysis with 25 samples and 36 effect sizes, and observed that males outperformed females with a small effect size (d = 0.22).

Another example is the study by Bosco et al. (2004) with 107 psychology students. A visual working memory test was employed, based on the *Visual Patterns Test* by Della Sala et al. (1999). Also, the Corsi Block Tapping Test (spatial working memory) was included. Results showed that men outperformed women in both the visual and the spatial working memory tests. Similar findings were reported with the original version of the Visual Patterns Test. In this study by Della Sala et al. (1999), a sample of 345 participants (54% females) revealed sex difference favoring men over women, but the difference was small.

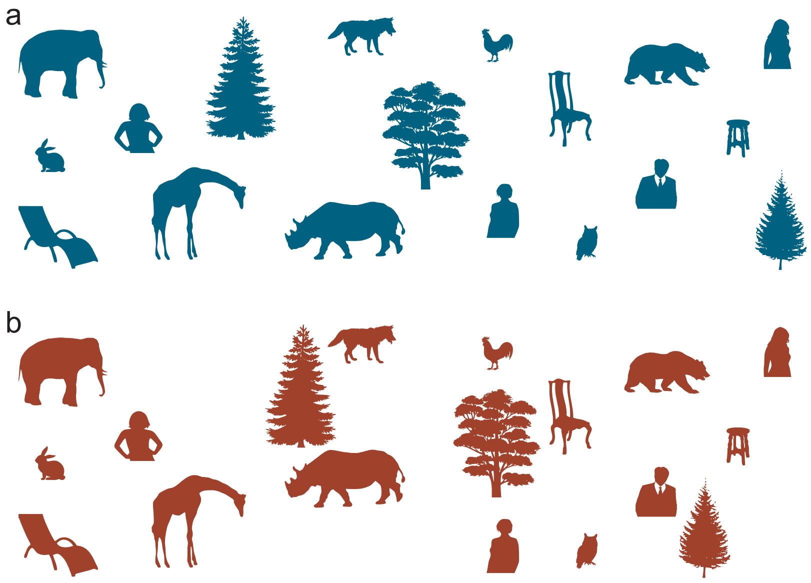


Fig. 4.2 Adapted item from an Object Location Memory task, showing (**a**) stimulus display and (**b**) test display where the trees have been displaced. Note that this is not an actual item, but an adaptation

Other visual working memory instruments are those measuring *object location memory* (e.g., Eals and Silverman 1994; Epting and Overman 1998; cf. Hammond et al. 2019; Kessels et al. 1999), an ability to compare a stimulus visual display of elements to a test display and judge which elements have been moved between both displays (see an example in Fig. 4.2). These instruments show peculiar effects. In contrast to most of the findings of visuospatial processing tasks, in which men tend to show higher scores, the instruments of Object Location Memory tend to show the opposite direction of effects.

For example, Voyer et al. (2007) conducted a meta-analysis of 86 effect sizes for object location memory tasks and observed an overall small effect size ($d = 0.27$) favorable to women. More currently, concerning simple location tasks (typically involving one object and short memorizing times), Voyer et al. (2017) reported a meta-analysis with nine samples and 26 effect sizes. It was also observed that in these less difficult location tasks, women outperformed men with a small to medium effect size ($d = 0.35$).

An important finding, not included in this meta-analysis, was provided in the large study ($N > 245{,}000$; 47% females) by Silverman et al. (2007), which collected data from participants attempting an Object Location Memory task in 40 countries and from seven self-identified ethnic groups. Results revealed significantly higher scores for the females of all the ethnicities and 35 of the 40 countries. The overall effect represented a small size ($d = 0.31$).

An explanation why women excel in these tasks is the *verbal memory hypothesis*, which predicts that the greater verbal ability of women (see Reilly et al. 2019) would allow them to add helpful verbal tags to the visuospatial test elements. For example, Choi and L'Hirondelle (2005) used novel tasks of object locations with 111 psychology undergraduates (55% females). One task employed images of nonsense object (difficult to verbally tag) and the other used images of ordinary objects (easy to verbally tag). In both tasks, participants had to memorize the display of images. After this, they had to replace each image in the right location, from memory. Also, verbal and visuospatial abilities were measured, and results showed that women excelled in the verbal instrument and men excelled in the visuospatial tests.

In the study, regarding the object location tasks, scores showed an interaction: Men presented higher scores with the nonsense objects, but females presented higher scores with the common objects. As predicted by the verbal memory hypothesis, women, who had a higher verbal score, might have relied more on verbally labeling the objects, and thus they achieved higher performance with the ordinary objects that were easier to tag. However, since the verbal strategy was less effective with nonsense objects, in this case, visuospatial processing was more effective. Consequently, men, who outperformed women in the other visuospatial tests, presented higher scores than women in the object location task with nonsense images.

In contrast, Lejbak et al. (2009), who investigated university students' performance on a task memorizing pairs of elements on display, showed that women outperformed men, independently of the ease to tag the items verbally. In fact, the female advantage was observed in the three types of graphics shown in the items, including those easier to verbally label (everyday objects and familiar shapes) and those more difficult for this verbal strategy (uncommon shapes).

These different dependencies on verbal strategies could explain why object location tasks do not always show sex differences. An example of null sex effects is the study with 64 university students (50% females) by Postma et al. (2004), who showed no significant sex differences in the two object location memory formats tested, namely, the traditional pen-and-paper task and a computerized version. Similarly, in two experiments with undergraduates (50% females), Nairne et al. (2012) reported no sex differences in object location memory tasks showing 8 line drawing of either food elements (Experiment 1, $N = 52$) or animals (Experiment 2, $N = 72$). This nil sex effects were observed both when giving survival or no survival instructions to the participants (see also Castro-Alonso et al. this volume-c, Chap. 7). Similarly, in a study with 47 university students (57% females), in which Epting and Overman (1998) investigated sex differences and the effects of hormones on visuospatial tests, men outperformed women on the 2D mental rotation task, but there were no sex differences in the Object Location Memory test.

4.1.5 Dual Visuospatial Tasks of Working Memory

As most of the evidence gravitates toward mental rotation favoring men and object location memory favoring women, there is less research showing sex differences with instruments such as *dual visuospatial tasks of working memory*. As described in Castro-Alonso and Atit (this volume, Chap. 2), dual tasks of working memory include two tasks (see also Castro-Alonso et al. 2018a). The main one is a *memory task*, in which different memory elements are shown in order, and they must be remembered in the order of presentation. The secondary task, which is interspaced between the memory task, is the *processing task*, where a Yes/No answer is usually expected (e.g., "Is this visual equation logical?"). Different standard tests use a diversity of memory and processing stimuli (see Castro-Alonso et al. this volume-a, Chap. 8). Here, we briefly describe two studies that employed visuospatial stimuli and investigated sex differences.

Investigating a large sample ($N > 5{,}500$) of participants, Redick et al. (2012) measured sex differences in the Symmetry Span Task. In this test, the memory task involves remembering where the filled square was positioned in a pattern of empty squares. The typical processing task is to judge whether different patterns of squares are symmetrical or not. Results for the memory task showed a small sex effect ($d = 0.26$) favoring men. For the processing component, there were no sex differences. Analogously, Geiger and Litwiller (2005) investigated 63 university students (76% females) attempting cognitive tasks. Results on a dual visuospatial task with rotated and mirror-reversed letters were favorable to men in the memory task.

In conclusion, several visuospatial processing tests show a different degree of sex influence. The tasks more favorable to men are mental rotations, notably 3D mental rotation tasks. However, the whole spectrum of visuospatial processing tasks is more favorable to men. The only exception where women tend to outscore men is in the visual working memory tasks of object location memory. Explanations for these sex differences in visuospatial processing are provided next.

4.2 Sociocultural and Biological Explanations

As described by Halpern (2006), explanations about sex differences on cognitive abilities are generally rooted in a false dichotomy of *sociocultural* vs. *biological* causes. For example, a myth about sex differences in visuospatial processing abilities tends to give precedence of fixed biological factors over malleable social variables (see Newcombe and Stieff 2011). Similarly, sex differences in other cognitive variables also show research streams that favor one pole over the other (see Eagly and Wood 2013). However, any cognitive performance is caused by biological variables influencing sociocultural experiences, which also shape back the biological factors. Thus, is a complex integrative mechanism where both sociocultural and biological roles are involved (see also Levine et al. 2016).

Nevertheless, the dichotomy is persistent among researchers because an alternative integrative approach would require interdisciplinarity, which is more difficult than dealing with the causes separately (see Eagly and Wood 2013). As such, although both *nurture* (socioculture) and *nature* (biology) causes should be considered together for a robust explanation of sex differences on visuospatial processing abilities, the evidence tends to be disaggregated into the poles. For this reason, we will also consider them separately here. Starting with sociocultural causes of sex differences in visuospatial processing, we will describe *visuospatial experience* (Sect. 4.2.1) and *stereotype threat* (Sect. 4.2.2). After this, we will address the biological cause of *hormones* (Sect. 4.2.3).

4.2.1 Visuospatial Experience

A greater and richer visuospatial experience for men than for women could be a sociocultural explanation for the sex differences observed in mental rotations and other visuospatial processing tasks. Although the evidence is generally correlational, it supports that better outcomes on visuospatial processing tests as an adult can be at least partially explained by a rich visuospatial experience from young ages. As shown in Table 4.2, we grouped these experiences as: (a) *sports and hobbies*, (b) *toys and games*, and (c) *computers and videogames*.

Addressing the type of sports and hobbies, Newcombe et al. (1983) developed a survey for high school and university students regarding participation in different spatial activities. The survey included 81 spatial activities: 40 regarded as masculine (e.g., basketball and carpentry), 21 considered feminine (e.g., ballet and knitting), and 20 considered neutral (e.g., volleyball and photography). Nazareth et al. (2013) conducted a mediation analysis to investigate if these sports and hobbies experienced when teenagers could help to explain the performance as adults on the Mental Rotations Test. Results indicated that being a man predicted successful performance on the 3D test. Notably, it was also observed that this model presented a better fit when the variable *number of previous masculine spatial activities* was included.

In addition to the type of spatial sport and hobby practiced, there are indications that *any* experience with sports and hobbies is more effective for cognitive processing than a sedentary lifestyle (see Castro-Alonso et al. this volume-c, Chap. 7; but see Jansen et al. 2016). For example, Voyer and Jansen (2017) conducted a meta-analysis of 33 samples and 62 effect sizes, to investigate the relationship between: (a) music and sports experience, and (b) tests of spatial ability. They observed an overall small to medium effect ($d = 0.38$), in which individuals with extensive practice in activities such as combat sports, gymnastics, dance, and music, showed higher spatial ability scores than subjects with no motor expertise.

Considering the type of toys and games, Jirout and Newcombe (2015) studied a large sample (N = 847) of 4- to 7-year-old children, in which spatial ability was

Table 4.2 Types and examples of visuospatial activities influencing sex differences

Type	Examples
Sports and hobbies	Basketball, combat, carpentry
Toys and games	Bicycles, swings, blocks, puzzles
Computers and videogames	Practice with computers, proficiency in spatial videogames

assessed with a standard pen-and-paper instrument. In addition, the parents reported how frequently their children played with various categories of toys and games. Results indicated that boys outperformed girls in the spatial ability test, after controlling for several cognitive variables. It was also observed that boys were reported as playing more frequently than girls in the following two categories: (a) bicycles, scooters, skateboards, and swings; and (b) blocks, puzzles, and board games. Levine et al. (2005) investigated 547 school students (50% females) from different socioeconomic backgrounds. The study showed that boys and girls from lower status showed equally low scores on a mental rotation task. In contrast, at higher socioeconomic backgrounds, where the scores were higher for all, boys outperformed girls. As suggested in the study, these findings supported that wealthier boys could have access to more expensive toys and games promoting spatial skills, as compared to poorer boys. It was assumed that girls, even from the higher socioeconomic status, were less involved in these somewhat expensive spatial activities with toys and games.

Recently, Moè et al. (2018) examined Mental Rotations Tests performance in 176 university students (54% females) from either science (chemistry, physics, mathematics) or nonscience (education, languages, philosophy) disciplines. The participants also rated their childhood preference for spatial toys (e.g., blocks and puzzles) and non-spatial toys (e.g., puppets and board games). Results showed that the females showing the highest mental rotation scores were those in science disciplines and those who had played with spatial toys.

Regarding the possible influence of computers and videogames, the review by Verdine et al. (2014) is broad enough to include these virtual experiences and the spatial toys and games just described. As such, the study reviewed different spatial activities that were effective in promoting the visuospatial abilities of young children, both at home and in preschool. These activities included spatial digital platforms and videogames, construction blocks, and jigsaw puzzles.

Another example is the meta-analysis by Cai et al. (2017) investigating sex differences on attitudes toward technology. This analysis of 87 comparisons (50 studies from the years 1997 to 2014), revealed small but significant effect sizes for *belief* (believing in the positive uses of technology) and *self-efficacy* (confidence in one's ability to use technology) favoring men over women. This men's higher technology self-efficacy may be partially explained by the findings of Drabowicz (2014) from adolescents of 39 countries completing the Program for International Student Assessment (PISA). Results of these questionnaires revealed that boys reported more frequent computer use than girls.

Roberts and Bell (2000) tested 44 psychology university students (52% females) attempting a computer mental rotation task with 2D shapes. In addition to researching sex differences, the authors assessed if familiarization with the computer influenced mental rotation performance. As expected, in the group that had not been familiarized with the computer before the test, males were faster than females on the mental rotation computer test. However, in the group that had time to know the computer, there were no sex differences on the computer mental rotations. As discussed by the authors, being knowledgeable with computers may have been more critical for this 2D computer task than being capable of mental rotation.

To include a study with other visuospatial processing abilities, the meta-analysis for different visuospatial tasks conducted by Voyer et al. (2017) showed that computerized tests drove the small overall effect size that favored men. When comparing computer-based versus pen-and-paper tests, it was reported that only the computer instruments produced significant effects, as the paper tests produced no sex differences. In other words, women were more challenged by the computer tasks.

4.2.2 *Stereotype Threat*

As reviewed in Spencer et al. (2016), in a *stereotype threat* situation, the affected person (e.g., Woman A) tries to avoid confirming a negative stereotype (e.g., women are bad at maths). In attempting to disconfirm the stereotype, this overthinking taxes working memory beyond its limits, resulting in a final negative result (e.g., Woman A having a bad math score). The stereotype threat literature dealing with sex effects was arguably started by Spencer et al. (1999) with females' underperformance in mathematical tasks (see also Nguyen and Ryan 2008).

Later research tackled related tasks demanding visuospatial abilities, as these have also the label of being difficult to women. An example of more confidence in spatial processing in men than in women is the meta-analysis by Syzmanowicz and Furnham (2011) studying 10,689 participants (57% females) self-estimating their spatial intelligence. Analyzing 56 comparisons, the overall effect size was medium ($d = 0.43$) for men outperforming women.

Due to this confidence of men in their visuospatial abilities, sex stereotypes about these abilities tend to be harmful to women only. Sometimes, by just being in a threat scenario, such as in a mixed-sex location attempting a spatial test, women are negatively affected. This would be an *implicit* sex threat situation. In contrast, giving framing instructions before the spatial test, in other words, giving indications that men perform better, results in an *explicit* threat situation. As shown in Table 4.3, we categorized sex stereotype threats by these two degrees.

Implicit framing instructions involve mentioning the sex of the participants before a visuospatial test but not giving an explicit comment on which sex generally performs better on the task. For example, McGlone and Aronson (2006) investigated 90 undergraduates (50% females) attempting the Mental Rotations Test after

Table 4.3 Degrees of sex stereotype threats and examples of framing instructions that could trigger these effects

Degree	Example of framing instruction
Implicit	"Write your sex here"
Explicit	"Which sex can imagine abstract objects and rotate them in mind?"
	"Men are better at mental rotation tasks"

a brief questionnaire had emphasized their sex. Results on the rotation task showed that priming to consider their sex impaired women and was beneficial for men.

Implicit threats can also be activated by the stimuli used in the visuospatial tests. For example, stimuli perceived as masculine could induce a greater implicit threat scenario than feminine or neutral stimuli. For an example with children, Ruthsatz et al. (2017) reported that 144 fourth graders (47% females) rated cube figures in a mental rotation test as male-stereotyped and pellet figures as female-stereotyped. The results showed the prediction for an implicit threat situation: Boys solely outperformed girls in tasks with the "masculine" cube figures rotated in depth, while there was no significant sex difference with the "feminine" pellet-figure items.

Although less investigated than for mental rotation, there are also stereotype effects with other visuospatial tasks. For example, regarding field independence, in a study with 166 (50% females) undergraduates, Drążkowski et al. (2017) assessed the participants' performance in the Group Embedded Figures Test. Notably, the authors compared field independence between participants who wrote down their sex either before or after attempting the test. Even such a minor intervention as reporting the sex beforehand was sufficient to elicit negative stereotypes in women, as they showed lower scores than men who reported their sex previously. In contrast, there were no significant differences in field independence when the sex was reported after the spatial ability test.

In contrast, an explicit sex threat involves, for example, mentioning which sex tend to show better performance on a specific visuospatial task. In a study with 114 adults (52% females), Hausmann et al. (2009) employed instruments to measure mental rotations in 3D (the Mental Rotations Tests) and 2D (the Mirror Pictures Test). Crucially, participants in the experimental condition read a description of a person's capacities (e.g., "…can rotate abstract objects mentally…"; "…can imagine common objects from different perspectives") and estimated the probability that the person was male or female. (In contrast, the control group estimated probabilities of being a North American or a European). For the experimental group with the sex stereotype activation, all participants tended to attribute spatial abilities more to males than to females. Moreover, this stereotype activation led men to increase and women to decrease their performance on the more difficult 3D mental rotation test, but this sex difference was not observed for the easier 2D mental rotation task.

Another example is from Heil et al. (2012), who studied the Mental Rotations Test performance of 300 adults (50% females) randomly assigned into three different stereotyping conditions, according to the instructions given before the task. In the *men are better* condition, the instructions for the Mental Rotation Test indicated that usually men scored higher on the test. In the *neutral* control condition, there was no indication of sexes affecting performance. In the *women are better* group, it was indicated that usually women scored higher than men. Although results showed that in all three groups men outperformed women, the effects were in the expected directions due to the framing instructions. The largest sex effect favoring men was in the *men are better* condition ($d = 1.17$), followed by the control group ($d = 0.86$), and followed by the *women are better* condition ($d = 0.27$, non-significant).

To explain stereotype threat effects, the *depletion of working memory* is a straightforward rationale, as it resonates with the cognitive load theory methods for avoiding working memory overload (see Castro-Alonso et al. this volume-b, Chap. 5). As defined by Hobfoll (1989) in the *conservation of resources* model for stress, the threat of losing valuable resources, such as academic reputation and self-esteem, is a stressful event. In this case, this psychological stress, in form of negative thoughts during spatial tasks in women, reduces available working memory to deal with the tasks.

Employing explicit threat instructions, Schmader and Johns (2003, Experiment 1) tested the working memory depletion hypothesis. In the experiment, 59 psychology undergraduates (47% females) completed maths working memory tests either in non-threat or threat conditions. In the non-threat condition, the instructions given for the working memory test did not indicate that sex influenced performance. In the threat group, the working memory test was described as related to sex differences and maths ability, known to be favorable to men. In the non-threat condition, there was no difference in performance on the working memory test between men and women, but in the threat condition, women (but not men) showed lower scores on the working memory test. These findings support that stereotype threat is at least partially caused by a reduction in total working memory capacity available to process a cognitive task (see also Schmader et al. 2008).

4.2.3 Hormones

A natural cause to explain sex differences in visuospatial abilities is that men and women have distinct types and levels of *hormones*, such as males' testosterone. In the visuospatial processing research literature, the effects of hormones can be classified according to the age of the participants. The studies can involve *prenatal* individuals (organizational effects) or developed participants, such as *adults* (activational effects). Organizational effects influence the in utero development of cognitive structures, which more permanently would affect visuospatial processing abilities. In contrast, activational effects depend on fluctuating levels of hormones in adults and tend to be less irreversible.

As shown in Table 4.4, a consistent effect with samples of prenatal individuals is that testosterone tends to enable women in visuospatial tasks. This finding has been observed in two of the three types of studies described here, namely, *fetal levels* and *twins*. In other words, research with fetal hormone levels and twin comparisons are more conclusive for women than for men. For the third category of prenatal studies, *medical conditions*, the effects are positive for both sexes.

In contrast, for adult participants, the effects are more difficult to interpret, and the different types of studies show conflicting evidence. In other words, the types termed here as: (a) *testosterone measured*, (b) *testosterone administered*, and (c) *estradiol measured* are not giving a conclusive picture, yet (see also Quaiser-Pohl et al. 2016).

Table 4.4 Age of participants, types of studies, and effect for hormones influencing sex differences

Age	Types of studies	Effect
Prenatal	Fetal levels	Testosterone enables women
	Twins	Testosterone enables women
	Medical conditions	Testosterone enables women and men
Adult	Testosterone measured	Testosterone does not enable women
	Testosterone administered	Testosterone enables women
	Estradiol measured	Estradiol enables and hinders women

An example of prenatal research measuring fetal hormone levels is given by Grimshaw et al. (1995). The authors used data from fetal testosterone levels of 60 participants (48% females) to investigate if these prenatal levels affected later mental rotation performance. When the participants had turned 7 years, they were required to perform a computer 2D mental rotation task with cartoon illustrations of bears. As expected, it was observed that girls who had previously higher prenatal testosterone did the mental rotations faster than girls with lower testosterone levels. But, for boys, the results were in the unexpected opposite direction, as higher fetal testosterone was related to slower rates of mental rotation.

More conclusive evidence can be obtained with larger samples, usually employed in the second type of prenatal studies, those with twins. Investigating 804 young adult twins (59% females), Vuoksimaa et al. (2010) tested if the sex of the co-twin in prenatal development would affect later adult performance on the Mental Rotations Test. This investigation tested the *prenatal masculinization hypothesis*, which assumes that there can be an intrauterine exchange in testosterone between twins, and that females are exposed to the testosterone from their male co-twins. Consistent with the hypothesis, results revealed that females with male co-twins showed higher scores in the Mental Rotations Test as adults, as compared to females with female co-twins. For males, there were no significant differences between having a male or a female co-twin. Also, males with male co-twins scored higher in mental rotations than females with female co-twins. Moreover, regression analyses showed that the greater performance of females with male co-twins over females with female co-twins was not influenced by environmental factors, including gestational age and videogame experience.

Similarly, Heil et al. (2011, Experiment 1) investigated the scores in the Mental Rotations Test of adult women with a high school degree, and observed that, from the 200 twins analyzed, the 100 females with a male co-twin outperformed those 100 with a female co-twin. Critically to discard environmental factors, these females with a male co-twin presented higher mental rotation scores than 100 control females (non-twins) who were raised with a slightly older brother.

In short, both fetal levels and twins' studies tend to show that testosterone enables women performance in visuospatial tasks (e.g., mental rotation). The research involving medical developmental conditions also shows this enabling effect in women, but it also shows disabling effects in men with low testosterone. For example, Resnick et al. (1986) investigated 25 patients (68% females) with *congenital* *adrenal hyperplasia*, a medical condition that exposed them to abnormally high levels of testosterone during development. A battery of cognitive tests was used, including measures of mental rotation, mental folding, and field independence. Results showed that women with the medical condition outperformed unaffected control women on the Mental Rotations Test, the Card Rotations Test, and the Hidden Patterns Test. Similarly, Berenbaum et al. (2012) observed that women with congenital adrenal hyperplasia preferred significantly more traditional male activities and presented significantly higher scores on the Mental Rotations Test, compared to women without this condition.

Analogous to this medical condition in which women produce more testosterone, Hier and Crowley (1982) investigated men with the developmental condition of *idiopathic hypogonadotropic hypogonadism*, who present a lack of androgenization likely mediated by testosterone deficiency. In the study, 19 of these adult men with low testosterone levels were compared in three verbal and three spatial tests to 19 adult men with regular concentrations of the hormone. It was observed that performance on the verbal tests was equivalent between participants, but in the three spatial tests (including one instrument of mental rotation and one of field independence) the scores were lower in the groups of men with low testosterone.

Describing adult samples, the evidence with these participants includes studies in which circulating levels of testosterone were measured, and these concentrations were correlated with visuospatial processing performance. For example, with an adult sample of 114 participants (52% females), Hausmann et al. (2009) reported that free levels of testosterone (measured from the saliva) were the best predictors for men's performance in 3D and 2D mental rotation tasks. However, this predictive effect was not observed in women.

In a longitudinal study with 17 adult participants (41% females), Courvoisier et al. (2013) investigated if performance in the Mental Rotations Test was influenced by cyclic variation of hormone levels, for both men and women, over the lapse of 2 months. It was observed that the relationship between testosterone and mental rotation speed was different between the sexes: reaction times were slowest at medium concentrations of testosterone for males, whereas they were slowest at high concentrations of testosterone for females. Notably, after mental rotation training for 2 months, the hormones did not remain predicting performance. In other words, the effects of hormones were less important than those of training.

The second group of adult studies concerns the administration of testosterone. In the experiment by Aleman et al. (2004), 26 right-handed adult females received sublingually either testosterone or placebo, and 5 h later attempted the Mental Rotations Test. Results showed that testosterone caused higher mental rotations than placebo. To conclude from these two types of adult research, when measuring testosterone, the results suggest that the hormone is not as helpful as when the hormone is administered. This is somewhat contradictory.

To this confusing picture, the studies in which the hormone estradiol is measured do not help to reach an overall conclusion. For example, an experiment with 70 undergraduates (56% females) conducted by Hampson and Morley (2013) investigated the effects of estradiol on females. Taking salivary samples, a group with higher blood levels of estradiol was compared to a group with lower levels of the hormone. For the Mental Rotations Test, the group with *lower* estradiol concentrations presented higher outcomes. In contrast, for a visual working memory task, the females with *higher* estradiol presented higher results.

In short, the effects of hormones, particularly in adult participants, seem to be less conclusive than those of spatial experience or sex stereotype threats. In addition, as the longitudinal study by Courvoisier et al. (2013) showed, there are other variables more influential to visuospatial performance than hormone levels, such as training, described next.

4.3 Visuospatial Training to Reduce Sex Differences

Among the spatial ability myths described by Newcombe and Stieff (2011), one was that *spatial ability is fixed*. This myth assumes that spatial ability is genetically transmitted and cannot be modified with sociocultural experiences. However, as we described in the previous section, the evidence suggests that both biological and sociocultural factors play a role in visuospatial processing. For example, the recent meta-analysis of twin studies by King et al. (2019), in which 42 effect sizes were included, showed that, although visuospatial processing was largely heritable (biological), it was also dependent on environmental and sociocultural factors (although to a smaller extent).

Hence, as explained by Newcombe and Stieff (2011), spatial ability is not fixed, because it can be improved with training (see also Uttal et al. 2013). Moreover, this training can also be transferred to related spatial tasks (see Castro-Alonso and Uttal this volume, Chap. 3). More important for this review, visuospatial training could potentially reduce the sex gap unfavorable to women (see Levine et al. 2016).

Visuospatial training can take many forms. Examples of formal educational activities that are recommended by Wai and Kell (2017) to train visuospatial processing in health and natural science contexts include: (a) exploring 3D phenomena with science models, (b) doing manipulations and laboratory activities, and (c) analyzing 2D images and graphs. Informal activities recommended by Reilly et al. (2017) are: (a) sports, (b) model building, (c) construction blocks, and (d) computer games. Next, we describe studies in which several of these training activities did or did not reduce the sex differences that were observed before training.

4.3.1 Reducing the Sex Differences

Addressing mental rotation, Provo et al. (2002) reported that a course of canine anatomy was effective in reducing the sex gap in first-year veterinary students. The authors observed that men showed higher scores before the intervention in a test of 3D mental rotation, and that this sex difference disappeared by the end of the anatomy course, showing that women improved more than men with this kind of training. Recently, the experiment with 611 medicine university students (65% females) by Guimarães et al. (2019) investigated the effects of virtual human anatomy training on Mental Rotations Test performance. When comparing the tests scores obtained before and after the training, it was observed that post-training performance was higher and that the sex differences favoring men before the treatment had disappeared after the anatomy training.

Feng et al. (2007, Experiment 2) investigated 20 undergraduates (70% females) playing videogames for a total training of 10 h (during less than 4 weeks). It was observed that training with action videogames increased performance on standard tests of mental rotation and spatial attention. Notably, these positive effects were higher for women than for men.

Regarding research with several tasks, Wright et al. (2008) investigated 31 adults (55% females) practicing computer 3D mental rotation and mental folding, in 21 training sessions once daily. In addition to a training effect and a smaller but significant transfer effect between the two visuospatial tasks, it was also observed that the initial sex differences disappeared by the end of training. Also, Stericker and LeVesconte (1982) trained 45 psychology participants (53% females) with three different standard instruments, respectively measuring 3D mental rotation, mental folding, and field independence. The training consisted of six weekly sessions devoted to approximately 20 min per test. After the training, the students improved their original scores in all the tests, compared to a control condition. Notably, the original men advantage observed in the tests before training disappeared after the six sessions.

Lord (1987) examined 120 science undergraduates (approximately 50% women) attempting a 3D mental rotation task (the Cube Comparisons Test), a mental folding test (the Paper Folding Test), and an instrument of field independence (the Hidden Figures Test). A one-semester training that involved weekly spatial exercises proved to be adequate for mental rotation and mental folding, but not for field independence. Furthermore, the effects were higher in women, so the gender gap in mental rotation and mental folding, unfavorable to women at the start, was reduced after the training.

The last example also concerns field independence. Goldstein and Chance (1965) investigated training effects of 26 undergraduates (50% females) completing the Embedded Figures Test. At the onset, men outperformed women on this instrument. However, when finishing the training of eight blocks of trials, women improved more than men, producing that the sex differences disappeared.

4.3.2 Not Reducing the Sex Differences

About mental rotation, Peters et al. (1995) reported a study with 27 university students (70% females) from fields of science (biological and physical science, and engineering) and non-science (arts, social sciences, and humanities). The participants practiced the Mental Rotations Test once weekly, for a total training of 4 weeks. It was observed that men significantly outperformed women on the test.

Also, although training was effective in significantly improving the scores for the participants, it was equally effective for both sexes, so it could not diminish the original differences favoring men.

Terlecki et al. (2008) invited 180 psychology undergraduates (66% women) among the highest and lowest scorers on a survey of computer and videogame expertise (see Terlecki and Newcombe 2005) to participate in a videogame spatial training program. For 12 weeks, the *spatial* condition practiced with 3D and 2D versions of the videogame Tetris™, whereas the *non-spatial* control condition practiced with the card videogame of Solitaire. Results showed that the spatial condition was effective in increasing the scores on the Mental Rotations Test. However, the original sex gap between men and women was not significantly closed, and this null result was not affected by the participants' experiences with computers and videogames.

Concerning various abilities, Okagaki and Frensch (1994, Experiment 1) investigated the effects of 12 training sessions (6 h in total) with the videogame of Tetris on three pen-and-paper visuospatial processing tests: (a) the Cube Comparisons Test of 3D mental rotation, (b) the Card Rotations Test of 2D mental rotation, and (c) the Form Board Test of mental folding. The study, conducted on 57 introductory psychology undergraduates (51% females) inexperienced in Tetris, revealed initial sex differences favoring males in the three visuospatial tests and Tetris performance. After the 6 h of videogame training, only males' scores on the Cube Comparisons Test and the Form Board Test improved, but females did not improve in any test. These results showed an enlargement of the initial sex gap unfavorable to the females for these instruments of mental rotation and mental folding.

A conclusion from the visuospatial training studies is not straightforward, as there is evidence showing that the initial sex gap favorable to men: (a) reduces, (b) continues, and (c) enlarges. Although various encouraging results support visuospatial training as an effective strategy to reduce the sex gap, the different visuospatial tasks and training regimes do not show yet consistent findings.

4.4 Discussion

There are many different abilities controlled by the visuospatial processing components of working memory. These different visuospatial abilities show different directions and degrees of sex differences. Although they generally favor men, the ability known as object location memory is usually performed better by women. For most of the other visuospatial skills, in which men excel, mental rotation and mainly 3D mental rotation show the most consistent differences favoring males.

There are sociocultural (nurture) and biological (nature) causes to explain these differences. One sociocultural explanation for these differences favoring men is visuospatial experience, because men generally practice with spatial sports, hobbies, toys, and videogames more often than women. Another sociocultural reason is stereotype threat, as only females are disadvantaged in visuospatial testing situations where they do not want to fail. By overthinking to avoid confirming the stereotype that women are bad in visuospatial abilities, they may fail in the tests due to working memory overload. A biological explanation for these sex differences involves the different hormones that male and female produce, notably testosterone.

Visuospatial training could be a powerful method to reduce the sex gap unfavorable to women. Many different visuospatial activities, which can be included in formal and informal educational settings, have shown positive effects for diminishing the gap. For example, training with visuospatial tests, spatial toys, science activities, and videogames show encouraging findings. However, there are also negative findings in which visuospatial training is not as effective to favor women over men.

4.4.1 Instructional Implications for Health and Natural Sciences

A first instructional implication is that educators (e.g., lecturers and instructors) should be aware that visuospatial processing could be influenced by sex, sex stereotypes, and science stereotypes. Consequently, educators should encourage visuospatial training and visuospatial activities in the classroom (see Newcombe 2016; Wai and Kell 2017), as a way to circumvent these sex and stereotype effects.

A second implication, related to the first, stems from the fact that different visuospatial tasks will show different sex influence. Similarly, different visuospatial tasks will be required to learn about different health and natural science topics (cf. Castro-Alonso et al. 2019a). As such, educators should focus their efforts on training the most relevant visuospatial task for the science content or discipline involved.

A third implication regards stereotype threat. As suggested by Levine et al. (2016), the instructional efforts should concentrate on reducing the susceptibility to these negative stereotypes. For example, female students should see female models excelling in visuospatial tasks, as women role models are pivotal in health and natural sciences (e.g., Miller et al. 2015; Rochon et al. 2016; Young et al. 2013). Also, students should be made aware of the stereotype threats effects that could impair their visuospatial and science achievement.

A fourth implication, linked to the previous, also regards stereotype threat. In this case, the awareness is for educators. They should be aware of the implicit stereotype threat that they might be transferring to their students (cf. Rosenthal and Jacobson 1968). In consequence, the stereotypes that teachers and instructors enforce or alleviate will affect students' visuospatial performance and learning in the science fields.

A fifth implication is for parents, coaches, and educators in general who oversee young children. They should encourage these children to be involved in visuospatial sports and hobbies, as these activities provide positive effects on health and cognition.

4.4.2 Future Research Directions

We now note some future directions that research into sex differences and visuospatial processing might follow. The first direction concerns also investigating the effects of *gender*, and not only *sex* differences. As described in Torgrimson and Minson (2005), the primary difference between the two constructs is that sex is biological, and gender is more related to sociocultural representations. For example, future research could recruit males (sex variable) and compare individuals with different self-identities (gender variable, e.g., Reilly et al. 2016) attempting 3D mental rotations.

Secondly, as Choi and L'Hirondelle (2005) reported different sex outcomes on Object Location Memory due to verbal strategies, these could also be investigated in other visuospatial processing tests. For example, as described in Castro-Alonso et al. (this volume-a, Chap. 8), instruments such as the Corsi Block Tapping Test or the Visual Patterns Test can be programmed to show a number on each element to memorize. These numbers could be used as verbal labels to remember better the sequences or patterns of the tests. Whether these verbal strategies are more helpful to women or men could be investigated.

In third place, a promising approach would be to integrate sociocultural as well as biological research questions in one design to investigate the interacting effects of both possible reasons. Although Eagly and Wood (2013) note that this approach is difficult because it involves interdisciplinary research, we believe that its potential makes the attempts worthwhile.

As a fourth possible direction, we consider the influence of computer and videogame experience on sex differences. For example, research on instructional simulations and videogames about science (see Castro-Alonso and Fiorella this volume, Chap. 6) are promising future directions for sex effects and visuospatial processing. Similarly, particular learning scenarios that need visuospatial processing, such as learning health and natural sciences from visualizations, could also be studied (see Castro-Alonso et al. this volume-b, Chap. 5). For example, learning from instructional visualizations is influenced by sex or gender and visuospatial processing (e.g., Castro-Alonso et al. 2019b; Wong et al. 2015, 2018).

A fifth direction concerns sex stereotype threats. Future research could investigate if different degrees of threats, such as implicit versus explicit framing instructions, have different results on the visuospatial performance of the same population. Also, the effects of sex threats could be compared between different visuospatial processing abilities. For example, spatial working memory and object location tasks could be analyzed. Also, because working memory depletion can partially explain these adverse stereotyping effects, the duration and cognitive loads involved in this depletion (e.g., Chen et al. 2018) could also be investigated.

A sixth direction involves training effects on the different visuospatial processing abilities. For example, the favorable training effects for women on mental rotation seem to be larger than for field independence. Different training activities, such as videogaming versus sports, are also encouraging new directions for inquiry.

4.4.3 Conclusion

Sex differences in visuospatial abilities are harmful to the underperforming sex, as these abilities are needed to learn and flourish in the fields of health and natural sciences. Despite mental rotation consistently showing a sex difference favoring men, not all visuospatial abilities show the same direction and degree of effects. In contrast to the small to moderate differences favorable to men in most of the visuospatial abilities, Object Location Memory is usually performed better by women. Explanations for these differences are typically classified as sociocultural or biological, ranging from previous visuospatial experience to hormonal factors. As experience is a well-documented explanation, a way forward to diminish these sex gaps is to promote activities and experiences that can train the visuospatial abilities, such as sports, toy manipulations, and videogames. The goal is that visuospatial training and other solutions help both women and men to improve in the areas of health and natural sciences.

Acknowledgments Support from PIA–CONICYT Basal Funds for Centers of Excellence Project FB0003, and CONICYT Fondecyt 11180255, is gratefully acknowledged. The first author is thankful to Enrique Castro and Monseratt Ibáñez for their assistance.

References

Aleman, A., Bronk, E., Kessels, R. P. C., Koppeschaar, H. P. F., & van Honk, J. (2004). A single administration of testosterone improves visuospatial ability in young women. *Psychoneuroendocrinology, 29*(5), 612–617. https://doi.org/10.1016/S0306-4530(03)00089-1.

Berenbaum, S. A., Bryk, K. L. K., & Beltz, A. M. (2012). Early androgen effects on spatial and mechanical abilities: Evidence from congenital adrenal hyperplasia. *Behavioral Neuroscience, 126*(1), 86–96. https://doi.org/10.1037/a0026652.

Bodner, G. M., & Guay, R. B. (1997). The Purdue Visualization of Rotations Test. *The Chemical Educator, 2*(4), 1–17. https://doi.org/10.1007/s00897970138a.

Bosco, A., Longoni, A. M., & Vecchi, T. (2004). Gender effects in spatial orientation: Cognitive profiles and mental strategies. *Applied Cognitive Psychology, 18*(5), 519–532. https://doi.org/10.1002/acp.1000.

Cai, Z., Fan, X., & Du, J. (2017). Gender and attitudes toward technology use: A meta-analysis. *Computers & Education, 105*, 1–13. https://doi.org/10.1016/j.compedu.2016.11.003.

Campos, A., Pérez-Fabello, M. a. J., & Gómez-Juncal, R. o. (2004). Gender and age differences in measured and self-perceived imaging capacity. *Personality and Individual Differences, 37*(7), 1383–1389. https://doi.org/10.1016/j.paid.2004.01.008.

Castro-Alonso, J. C., & Atit, K. (this volume). Different abilities controlled by visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 23–51). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_2.

Castro-Alonso, J. C., & Fiorella, L. (this volume). Interactive science multimedia and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 145–173). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_6.

Castro-Alonso, J. C., & Uttal, D. H. (this volume). Science education and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 53–79). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_3.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018a). Computerized and adaptable tests to measure visuospatial abilities in STEM students. In T. Andre (Ed.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2017 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 337–349). Cham: Springer. https://doi.org/10.1007/978-3-319-60018-5_33.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2018b). Learning symbols from permanent and transient visual presentations: Don't overplay the hand. *Computers & Education, 116*, 1–13. https://doi.org/10.1016/j.compedu.2017.08.011.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2019a). Visuospatial tests and multimedia learning: The importance of employing relevant instruments. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (pp. 89–99). New York: Routledge. https://doi.org/10.4324/9780429283895-8.

Castro-Alonso, J. C., Wong, M., Adesope, O. O., Ayres, P., & Paas, F. (2019b). Gender imbalance in instructional dynamic versus static visualizations: A meta-analysis. *Educational Psychology Review*, *31*(2), 361–387. https://doi.org/10.1007/s10648-019-09469-1.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (this volume-a). VAR: A battery of computer-based instruments to measure visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 207–229). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_8.

Castro-Alonso, J. C., Ayres, P., & Sweller, J. (this volume-b). Instructional visualizations, cognitive load theory, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 111–143). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_5.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (this volume-c). Embodied cognition, science education, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 175–205). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_7.

Chen, O., Castro-Alonso, J. C., Paas, F., & Sweller, J. (2018). Extending cognitive load theory to incorporate working memory resource depletion: Evidence from the spacing effect. *Educational Psychology Review, 30*(2), 483–501. https://doi.org/10.1007/s10648-017-9426-2.

Cherney, I. D. (2008). Mom, let me play more computer games: They improve my mental rotation skills. *Sex Roles, 59*(11–12), 776–786. https://doi.org/10.1007/s11199-008-9498-z.

Choi, J., & L'Hirondelle, N. (2005). Object location memory: A direct test of the verbal memory hypothesis. *Learning and Individual Differences, 15*(3), 237–245. https://doi.org/10.1016/j.lindif.2005.02.001.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale: Erlbaum.

Courvoisier, D. S., Renaud, O., Geiser, C., Paschke, K., Gaudy, K., & Jordan, K. (2013). Sex hormones and mental rotation: An intensive longitudinal investigation. *Hormones and Behavior, 63*(2), 345–351. https://doi.org/10.1016/j.yhbeh.2012.12.007.

Darling, S., Della Sala, S., Logie, R. H., & Cantagallo, A. (2006). Neuropsychological evidence for separating components of visuo–spatial working memory. *Journal of Neurology, 253*(2), 176–180. https://doi.org/10.1007/s00415-005-0944-3.

Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwelding visuo–spatial memory. *Neuropsychologia, 37*(10), 1189–1199. https://doi.org/10.1016/S0028-3932(98)00159-6.

Drabowicz, T. (2014). Gender and digital usage inequality among adolescents: A comparative study of 39 countries. *Computers & Education, 74*, 98–111. https://doi.org/10.1016/j.compedu.2014.01.016.

Drążkowski, D., Szwedo, J., Krajczewska, A., Adamczuk, A., Piątkowski, K., Jadwiżyc, M., et al. (2017). Women are not less field independent than men—The role of stereotype threat. *International Journal of Psychology, 52*(5), 415–419. https://doi.org/10.1002/ijop.12238.

Eagly, A. H., & Wood, W. (2013). The nature–nurture debates: 25 years of challenges in understanding the psychology of gender. *Perspectives on Psychological Science, 8*(3), 340–357. https://doi.org/10.1177/1745691613484767.

Eals, M., & Silverman, I. (1994). The Hunter-Gatherer theory of spatial sex differences: Proximate factors mediating the female advantage in recall of object arrays. *Ethology and Sociobiology, 15*(2), 95–105. https://doi.org/10.1016/0162-3095(94)90020-5.

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Kit of factor-referenced cognitive tests*. Princeton: Educational Testing Service.

Epting, L. K., & Overman, W. H. (1998). Sex-sensitive tasks in men and women: A search for performance fluctuations across the menstrual cycle. *Behavioral Neuroscience, 112*(6), 1304–1317. https://doi.org/10.1037/0735-7044.112.6.1304.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science, 18*(10), 850–855. https://doi.org/10.1111/j.1467-9280.2007.01990.x.

Ferguson, A. M., Maloney, E. A., Fugelsang, J., & Risko, E. F. (2015). On the relation between math and spatial ability: The case of math anxiety. *Learning and Individual Differences, 39*, 1–12. https://doi.org/10.1016/j.lindif.2015.02.007.

Geiger, J. F., & Litwiller, R. M. (2005). Spatial working memory and gender differences in science. *Journal of Instructional Psychology, 32*(1), 49–57.

Goldstein, A. G., & Chance, J. E. (1965). Effects of practice on sex-related differences in performance on Embedded Figures. *Psychonomic Science, 3*(1–12), 361–362. https://doi.org/10.3758/bf03343180.

Grimshaw, G. M., Sitarenios, G., & Finegan, J.-A. K. (1995). Mental rotation at 7 years: Relations with prenatal testosterone levels and spatial play experiences. *Brain and Cognition, 29*(1), 85–100. https://doi.org/10.1006/brcg.1995.1269.

Guillot, A., Champely, S., Batier, C., Thiriet, P., & Collet, C. (2007). Relationship between spatial abilities, mental rotation and functional anatomy learning. *Advances in Health Sciences Education, 12*(4), 491–507. https://doi.org/10.1007/s10459-006-9021-7.

Guimarães, B., Firmino-Machado, J., Tsisar, S., Viana, B., Pinto-Sousa, M., Vieira-Marques, P., et al. (2019). The role of anatomy computer-assisted learning on spatial abilities of medical students. *Anatomical Sciences Education, 12*(2), 138–153. https://doi.org/10.1002/ase.1795.

Halpern, D. F. (2006). Assessing gender gaps in learning and academic achievement. In P. A. Alexander & P. H. Winne (Eds.), *Handbook of educational psychology* (2nd ed., pp. 635–653). Mahwah: Lawrence Erlbaum Associates.

Hammond, A. G., Murphy, E. M., Silverman, B. M., Bernas, R. S., & Nardi, D. (2019). No environmental context-dependent effect, but interference, of physical activity on object location memory. *Cognitive Processing, 20*(1), 31–43. https://doi.org/10.1007/s10339-018-0875-4.

Hampson, E., & Morley, E. E. (2013). Estradiol concentrations and working memory performance in women of reproductive age. *Psychoneuroendocrinology, 38*(12), 2897–2904. https://doi.org/10.1016/j.psyneuen.2013.07.020.

Hausmann, M., Schoofs, D., Rosenthal, H. E. S., & Jordan, K. (2009). Interactive effects of sex hormones and gender stereotypes on cognitive sex differences—A psychobiosocial approach. *Psychoneuroendocrinology, 34*(3), 389–401. https://doi.org/10.1016/j.psyneuen.2008.09.019.

Hegarty, M. (2018). Ability and sex differences in spatial thinking: What does the mental rotation test really measure? *Psychonomic Bulletin & Review, 25*(3), 1212–1219. https://doi.org/10.3758/s13423-017-1347-z.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34*(2), 151–176. https://doi.org/10.1016/j.intell.2005.09.005.

Hegarty, M., Keehner, M., Khooshabeh, P., & Montello, D. R. (2009). How spatial abilities enhance, and are enhanced by, dental education. *Learning and Individual Differences, 19*(1), 61–70. https://doi.org/10.1016/j.lindif.2008.04.006.

Heil, M., Kavšek, M., Rolke, B., Beste, C., & Jansen, P. (2011). Mental rotation in female fraternal twins: Evidence for intra-uterine hormone transfer? *Biological Psychology, 86*(1), 90–93. https://doi.org/10.1016/j.biopsycho.2010.11.002.

Heil, M., Jansen, P., Quaiser-Pohl, C., & Neuburger, S. (2012). Gender-specific effects of artificially induced gender beliefs in mental rotation. *Learning and Individual Differences, 22*(3), 350–353. https://doi.org/10.1016/j.lindif.2012.01.004.

Hier, D. B., & Crowley, W. F. (1982). Spatial ability in androgen-deficient men. *New England Journal of Medicine, 306*(20), 1202–1205. https://doi.org/10.1056/nejm198205203062003.

Hobfoll, S. E. (1989). Conservation of resources: A new attempt at conceptualizing stress. *American Psychologist, 44*(3), 513–524. https://doi.org/10.1037/0003-066X.44.3.513.

Hyde, J. S. (2014). Gender similarities and differences. *Annual Review of Psychology, 65*, 373–398. https://doi.org/10.1146/annurev-psych-010213-115057.

Jansen, P., Zayed, K., & Osmann, R. (2016). Gender differences in mental rotation in Oman and Germany. *Learning and Individual Differences, 51*, 284–290. https://doi.org/10.1016/j.lindif.2016.08.033.

Jirout, J. J., & Newcombe, N. S. (2015). Building blocks for developing spatial skills: Evidence from a large, representative U.S. sample. *Psychological Science, 26*(3), 302–310. https://doi.org/10.1177/0956797614563338.

Kessels, R. P. C., Postma, A., & de Haan, E. H. F. (1999). Object relocation: A program for setting up, running, and analyzing experiments on memory for object locations. *Behavior Research Methods, Instruments, & Computers, 31*(3), 423–428. https://doi.org/10.3758/bf03200721.

Kessels, R. P. C., van Zandvoort, M. J. E., Postma, A., Kappelle, L. J., & de Haan, E. H. F. (2000). The Corsi Block-Tapping Task: Standardization and normative data. *Applied Neuropsychology, 7*(4), 252–258. https://doi.org/10.1207/S15324826AN0704_8.

King, M. J., Katz, D. P., Thompson, L. A., & Macnamara, B. N. (2019). Genetic and environmental influences on spatial reasoning: A meta-analysis of twin studies. *Intelligence, 73*, 65–77. https://doi.org/10.1016/j.intell.2019.01.001.

Lejbak, L., Vrbancic, M., & Crossley, M. (2009). The female advantage in object location memory is robust to verbalizability and mode of presentation of test stimuli. *Brain and Cognition, 69*(1), 148–153. https://doi.org/10.1016/j.bandc.2008.06.006.

Lejbak, L., Crossley, M., & Vrbancic, M. (2011). A male advantage for spatial and object but not verbal working memory using the n-back task. *Brain and Cognition, 76*(1), 191–196. https://doi.org/10.1016/j.bandc.2010.12.002.

Levine, S. C., Vasilyeva, M., Lourenco, S. F., Newcombe, N. S., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psychological Science, 16*(11), 841–845. https://doi.org/10.1111/j.1467-9280.2005.01623.x.

Levine, S. C., Foley, A., Lourenco, S., Ehrlich, S., & Ratliff, K. (2016). Sex differences in spatial cognition: Advancing the conversation. *Wiley Interdisciplinary Reviews: Cognitive Science, 7*(2), 127–155. https://doi.org/10.1002/wcs.1380.

Levinson, A. J., Weaver, B., Garside, S., McGinn, H., & Norman, G. R. (2007). Virtual reality and brain anatomy: A randomised trial of e-learning instructional designs. *Medical Education, 41*(5), 495–501. https://doi.org/10.1111/j.1365-2929.2006.02694.x.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*(6), 1479–1498. https://doi.org/10.2307/1130467.

Loftus, J. J., Jacobsen, M., & Wilson, T. D. (2017). Learning and assessment with images: A view of cognitive load through the lens of cerebral blood flow. *British Journal of Educational Technology, 48*(4), 1030–1046. https://doi.org/10.1111/bjet.12474.

Lord, T. R. (1987). A look at spatial abilities in undergraduate women science majors. *Journal of Research in Science Teaching, 24*(8), 757–767. https://doi.org/10.1002/tea.3660240808.

Maeda, Y., & Yoon, S. Y. (2013). A meta-analysis on gender differences in mental rotation ability measured by the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R). *Educational Psychology Review, 25*(1), 69–94. https://doi.org/10.1007/s10648-012-9215-x.

Masters, M. S., & Sanders, B. (1993). Is the gender difference in mental rotation disappearing? *Behavior Genetics, 23*(4), 337–341. https://doi.org/10.1007/BF01067434.

Mayer, R. E., & Massa, L. J. (2003). Three facets of visual and verbal learners: Cognitive ability, cognitive style, and learning preference. *Journal of Educational Psychology, 95*(4), 833–846. https://doi.org/10.1037/0022-0663.95.4.833.

McGlone, M. S., & Aronson, J. (2006). Stereotype threat, identity salience, and spatial reasoning. *Journal of Applied Developmental Psychology, 27*(5), 486–493. https://doi.org/10.1016/j.appdev.2006.06.003.

Miller, D. I., Eagly, A. H., & Linn, M. C. (2015). Women's representation in science predicts national gender-science stereotypes: Evidence from 66 nations. *Journal of Educational Psychology, 107*(3), 631–644. https://doi.org/10.1037/edu0000005.

Moè, A., Jansen, P., & Pietsch, S. (2018). Childhood preference for spatial toys. Gender differences and relationships with mental rotation in STEM and non-STEM students. *Learning and Individual Differences, 68*, 108–115. https://doi.org/10.1016/j.lindif.2018.10.003.

Moreau, D., Clerc, J., Mansy-Dannay, A., & Guerrien, A. (2012). Enhancing spatial ability through sport practice. *Journal of Individual Differences, 33*(2), 83–88. https://doi.org/10.1027/1614-0001/a000075.

Nairne, J. S., VanArsdall, J. E., Pandeirada, J. N. S., & Blunt, J. R. (2012). Adaptive memory: Enhanced location memory after survival processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(2), 495–501. https://doi.org/10.1037/a0025728.

Nazareth, A., Herrera, A., & Pruden, S. M. (2013). Explaining sex differences in mental rotation: Role of spatial activity experience. *Cognitive Processing, 14*(2), 201–204. https://doi.org/10.1007/s10339-013-0542-8.

Newcombe, N. S. (2016). Thinking spatially in the science classroom. *Current Opinion in Behavioral Sciences, 10*, 1–6. https://doi.org/10.1016/j.cobeha.2016.04.010.

Newcombe, N. S., & Stieff, M. (2011). Six myths about spatial thinking. *International Journal of Science Education, 34*(6), 955–971. https://doi.org/10.1080/09500693.2011.588728.

Newcombe, N. S., Bandura, M. M., & Taylor, D. G. (1983). Sex differences in spatial ability and spatial activities. *Sex Roles, 9*(3), 377–386. https://doi.org/10.1007/bf00289672.

Nguyen, H.-H. D., & Ryan, A. M. (2008). Does stereotype threat affect test performance of minorities and women? A meta-analysis of experimental evidence. *Journal of Applied Psychology, 93*(6), 1314–1334. https://doi.org/10.1037/a0012702.

Nordvik, H., & Amponsah, B. (1998). Gender differences in spatial abilities and spatial activity among university students in an egalitarian educational system. *Sex Roles, 38*(11–12), 1009–1023. https://doi.org/10.1023/A:1018878610405.

Okagaki, L., & Frensch, P. A. (1994). Effects of video game playing on measures of spatial performance: Gender effects in late adolescence. *Journal of Applied Developmental Psychology, 15*(1), 33–58. https://doi.org/10.1016/0193-3973(94)90005-1.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*(1), 39–58. https://doi.org/10.1006/brcg.1995.1032.

Piccardi, L., Iaria, G., Ricci, M., Bianchini, F., Zompanti, L., & Guariglia, C. (2008). Walking in the Corsi test: Which type of memory do you need? *Neuroscience Letters, 432*(2), 127–131. https://doi.org/10.1016/j.neulet.2007.12.044.

Postma, A., Jager, G., Kessels, R. P. C., Koppeschaar, H. P. F., & van Honk, J. (2004). Sex differences for selective forms of spatial memory. *Brain and Cognition, 54*(1), 24–34. https://doi.org/10.1016/S0278-2626(03)00238-0.

Provo, J., Lamar, C., & Newby, T. (2002). Using a cross section to train veterinary students to visualize anatomical structures in three dimensions. *Journal of Research in Science Teaching, 39*(1), 10–34. https://doi.org/10.1002/tea.10007.

Quaiser-Pohl, C., Jansen, P., Lehmann, J., & Kudielka, B. M. (2016). Is there a relationship between the performance in a chronometric mental-rotations test and salivary testosterone and estradiol levels in children aged 9–14 years? *Developmental Psychobiology, 58*(1), 120–128. https://doi.org/10.1002/dev.21333.

Redick, T. S., Broadway, J. M., Meier, M. E., Kuriakose, P. S., Unsworth, N., Kane, M. J., et al. (2012). Measuring working memory capacity with automated complex span tasks. *European Journal of Psychological Assessment, 28*(3), 164–171. https://doi.org/10.1027/1015-5759/a000123.

Reilly, D., Neumann, D. L., & Andrews, G. (2016). Sex and sex-role differences in specific cognitive abilities. *Intelligence, 54*, 147–158. https://doi.org/10.1016/j.intell.2015.12.004.

Reilly, D., Neumann, D. L., & Andrews, G. (2017). Gender differences in spatial ability: Implications for STEM education and approaches to reducing the gender gap for parents and educators. In M. S. Khine (Ed.), *Visual-spatial ability in STEM education: Transforming research into practice* (pp. 195–224). Cham: Springer. https://doi.org/10.1007/978-3-319-44385-0_10.

Reilly, D., Neumann, D. L., & Andrews, G. (2019). Gender differences in reading and writing achievement: Evidence from the National Assessment of Educational Progress (NAEP). *American Psychologist*, *74*(4), 445–458. https://doi.org/10.1037/amp0000356.

Resnick, S. M., Berenbaum, S. A., Gottesman, I. I., & Bouchard, T. J. (1986). Early hormonal influences on cognitive functioning in congenital adrenal hyperplasia. *Developmental Psychology, 22*(2), 191–198. https://doi.org/10.1037/0012-1649.22.2.191.

Roberts, J. E., & Bell, M. A. (2000). Sex differences on a computerized mental rotation task disappear with computer familiarization. *Perceptual and Motor Skills, 91*(3f), 1027–1034. https://doi.org/10.2466/pms.2000.91.3f.1027.

Roberts, J. E., & Bell, M. A. (2003). Two- and three-dimensional mental rotation tasks lead to different parietal laterality for men and women. *International Journal of Psychophysiology, 50*(3), 235–246. https://doi.org/10.1016/s0167-8760(03)00195-8.

Rochon, P. A., Davidoff, F., & Levinson, W. (2016). Women in academic medicine leadership: Has anything changed in 25 years? *Academic Medicine, 91*(8), 1053–1056. https://doi.org/10.1097/acm.0000000000001281.

Rosenthal, R., & Jacobson, L. (1968). Pygmalion in the classroom. *The Urban Review, 3*(1), 16–20. https://doi.org/10.1007/bf02322211.

Ruggiero, G., Sergi, I., & Iachini, T. (2008). Gender differences in remembering and inferring spatial distances. *Memory, 16*(8), 821–835. https://doi.org/10.1080/09658210802307695.

Ruthsatz, V., Neuburger, S., Rahe, M., Jansen, P., & Quaiser-Pohl, C. (2017). The gender effect in 3D-mental-rotation performance with familiar and gender-stereotyped objects – A study with elementary school children. *Journal of Cognitive Psychology, 29*(6), 717–730. https://doi.org/10.1080/20445911.2017.1312689.

Sanchez, C. A., & Wiley, J. (2010). Sex differences in science learning: Closing the gap through animations. *Learning and Individual Differences, 20*(3), 271–275. https://doi.org/10.1016/j.lindif.2010.01.003.

Sanders, B., Soares, M. P., & D'Aquila, J. M. (1982). The sex difference on one test of spatial visualization: A nontrivial difference. *Child Development, 53*(4), 1106–1110. https://doi.org/10.2307/1129153.

Schmader, T., & Johns, M. (2003). Converging evidence that stereotype threat reduces working memory capacity. *Journal of Personality and Social Psychology, 85*(3), 440–452. https://doi.org/10.1037/0022-3514.85.3.440.

Schmader, T., Johns, M., & Forbes, C. (2008). An integrated process model of stereotype threat effects on performance. *Psychological Review, 115*(2), 336–356. https://doi.org/10.1037/0033-295X.115.2.336.

Silverman, I., Choi, J., & Peters, M. (2007). The hunter-gatherer theory of sex differences in spatial abilities: Data from 40 countries. *Archives of Sexual Behavior, 36*(2), 261–268. https://doi.org/10.1007/s10508-006-9168-6.

Spencer, S. J., Steele, C. M., & Quinn, D. M. (1999). Stereotype threat and women's math performance. *Journal of Experimental Social Psychology, 35*(1), 4–28. https://doi.org/10.1006/jesp.1998.1373.

Spencer, S. J., Logel, C., & Davies, P. G. (2016). Stereotype threat. *Annual Review of Psychology, 67*, 415–437. https://doi.org/10.1146/annurev-psych-073115-103235.

Stephenson, C. L., & Halpern, D. F. (2013). Improved matrix reasoning is limited to training on tasks with a visuospatial component. *Intelligence, 41*(5), 341–357. https://doi.org/10.1016/j.intell.2013.05.006.

Stericker, A., & LeVesconte, S. (1982). Effect of brief training on sex-related differences in visual–spatial skill. *Journal of Personality and Social Psychology, 43*(5), 1018–1029. https://doi.org/10.1037/0022-3514.43.5.1018.

Syzmanowicz, A., & Furnham, A. (2011). Gender differences in self-estimates of general, mathematical, spatial and verbal intelligence: Four meta analyses. *Learning and Individual Differences, 21*(5), 493–504. https://doi.org/10.1016/j.lindif.2011.07.001.

Terlecki, M. S., & Newcombe, N. S. (2005). How important is the digital divide? The relation of computer and videogame usage to gender differences in mental rotation ability. *Sex Roles, 53*(5–6), 433–441. https://doi.org/10.1007/s11199-005-6765-0.

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology, 22*(7), 996–1013. https://doi.org/10.1002/acp.1420.

Torgrimson, B. N., & Minson, C. T. (2005). Sex and gender: What is the difference? *Journal of Applied Physiology, 99*(3), 785–787. https://doi.org/10.1152/japplphysiol.00376.2005.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., et al. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352–402. https://doi.org/10.1037/a0028446.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2014). Finding the missing piece: Blocks, puzzles, and shapes fuel school readiness. *Trends in Neuroscience and Education, 3*(1), 7–13. https://doi.org/10.1016/j.tine.2014.02.005.

Vorstenbosch, M. A. T. M., Klaassen, T. P. F. M., Donders, A. R. T., Kooloos, J. G. M., Bolhuis, S. M., & Laan, R. F. J. M. (2013). Learning anatomy enhances spatial ability. *Anatomical Sciences Education, 6*(4), 257–262. https://doi.org/10.1002/ase.1346.

Voyer, D., & Jansen, P. (2016). Sex differences in chronometric mental rotation with human bodies. *Psychological Research, 80*(6), 974–984. https://doi.org/10.1007/s00426-015-0701-x.

Voyer, D., & Jansen, P. (2017). Motor expertise and performance in spatial tasks: A meta-analysis. *Human Movement Science, 54*, 110–124. https://doi.org/10.1016/j.humov.2017.04.004.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*(2), 250–270. https://doi.org/10.1037/0033-2909.117.2.250.

Voyer, D., Postma, A., Brake, B., & Imperato-McGinley, J. (2007). Gender differences in object location memory: A meta-analysis. *Psychonomic Bulletin & Review, 14*(1), 23–38. https://doi.org/10.3758/BF03194024.

Voyer, D., Voyer, S. D., & Saint-Aubin, J. (2017). Sex differences in visual-spatial working memory: A meta-analysis. *Psychonomic Bulletin & Review, 24*(2), 307–334. https://doi.org/10.3758/s13423-016-1085-7.

Vuoksimaa, E., Kaprio, J., Kremen, W. S., Hokkanen, L., Viken, R. J., Tuulio-Henriksson, A., et al. (2010). Having a male co-twin masculinizes mental rotation performance in females. *Psychological Science, 21*(8), 1069–1071. https://doi.org/10.1177/0956797610376075.

Wai, J., & Kell, H. J. (2017). What innovations have we already lost?: The importance of identifying and developing spatial talent. In M. S. Khine (Ed.), *Visual-spatial ability in STEM education: Transforming research into practice* (pp. 109–124). Cham: Springer. https://doi.org/10.1007/978-3-319-44385-0_6.

Witkin, H. A. (1949). The nature and importance of individual differences in perception. *Journal of Personality, 18*(2), 145–170. https://doi.org/10.1111/j.1467-6494.1949.tb01237.x.

Wong, M., Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015). Gender effects when learning manipulative tasks from instructional animations and static presentations. *Educational Technology & Society, 18*(4), 37–52.

Wong, M., Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018). Investigating gender and spatial measurements in instructional animation research. *Computers in Human Behavior, 89*, 446–456. https://doi.org/10.1016/j.chb.2018.02.017.

Woods, D. L., Wyma, J. M., Herron, T. J., & Yund, E. W. (2016). An improved spatial span test of visuospatial memory. *Memory, 24*(8), 1142–1155. https://doi.org/10.1080/09658211.2015.1076849.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review, 15*(4), 763–771. https://doi.org/10.3758/PBR.15.4.763.

Young, D. M., Rudman, L. A., Buettner, H. M., & McLean, M. C. (2013). The influence of female role models on women's implicit science cognitions. *Psychology of Women Quarterly, 37*(3), 283–292. https://doi.org/10.1177/0361684313482109.

Zell, E., Krizan, Z., & Teeter, S. R. (2015). Evaluating gender similarities and differences using metasynthesis. *American Psychologist, 70*(1), 10–20. https://doi.org/10.1037/a0038208.

Chapter 5
Instructional Visualizations, Cognitive Load Theory, and Visuospatial Processing

Juan C. Castro-Alonso, Paul Ayres, and John Sweller

There is ample evidence showing that instructional visualizations, both in static (e.g., illustrations and photographs) and in dynamic formats (e.g., animations and videos) can be engaging and fun for university students in the disciplines of health and natural sciences. For example, in reviewing studies of the health sciences, Houts et al. (2006) reported that large positive effects could be achieved by combining instructional texts with static or dynamic visualizations. The review showed that adding these instructional visualizations to the textual information increased participants' attention, comprehension, recall, and adherence (behavioral change).

With regards to static images, Hosler et al. (2011) investigated the effectiveness of a comic book in delivering content and engaging 98 undergraduates (61% females) in the biology topics of vision and evolution. Results showed increases in both knowledge of the topics and positive attitudes toward biology. With regards to dynamic visualizations, Jaffar (2012) asked 91 medicine and surgery undergraduates to rate their opinions about the instructional effectiveness of a YouTube™ channel showing videos of human anatomy. The videos included plastic models, cadaveric dissections, radiographs, PowerPoint™ presentations, and surgical procedures. Most participants (92%) agreed or strongly agreed that the style of the video channel was helpful to learn anatomy. Particularly, they valued the properties of *increasing understanding* (98%), *creating memorable images* (96%), and *all-day availability* (94%).

These examples show that studies employing both static and dynamic visualizations provide evidence that students enjoy these materials. Nevertheless, students' emotions and opinions are not always related to actual learning. For example, Mahmud et al. (2011) reported a study with 287 medicine and surgery undergraduates

---

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

P. Ayres · J. Sweller
School of Education, University of New South Wales, Sydney, Australia

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_5

(69% females) investigating the instructional effectiveness of dissection videos shown during classes and made available for later restudy. After the treatment of approximately 6 weeks, students' opinions on the videos were enthusiastic, but the anatomy test scores were not significantly altered. In other words, liking did not translate into learning.

Therefore, teachers, lecturers, and instructional designers need to be aware that emotions and motivation do not necessarily lead to more learning through instructional visualizations. A variable that must be considered for effective learning under these conditions is working memory processing. Although the instructional visualization literature provides examples of emotional and motivational factors affecting science learning and working memory processing (cf. Fraser et al. 2014), the focus of this chapter is not on this relationship. Instead, we will focus on working memory (cognitive) processing, specifically visuospatial processing, without including emotional or motivational influences. In particular, this chapter has three goals: (a) to show that instructional visualizations can optimize cognitive processing, and thus be effective tools for learning about health and natural sciences; (b) to describe cognitive methods for increasing the effectiveness of these instructional visualizations; and (c) to portray how visuospatial processing impacts on science learning through visualizations.

5.1 Science Learning Optimized Through Instructional Visualizations

There is a long tradition in the educational psychology literature (e.g., Calkins 1898; Shepard 1967) showing that visualizations tend to be easier to memorize than verbal information (spoken and written words). This cognitive advantage of instructional visualizations has been recognized by instructional designers who add visualizations to textual passages, as a way to improve learning. In fact, this combination of visual and verbal representations has generally been found to improve learning.

The review by Vekiri (2002) outlined two research avenues that support the use of this picture plus text combination. On the one hand, the *visual argument hypothesis* predicts that visualizations can involve less search for the relations between the learning elements, as compared to equivalent textual information. As such, visualizations require less working memory processing, so any additional resources can be allocated to understanding the texts. In contrast, pure textual information would not leave as many resources for in-depth processing.

On the other hand, *dual coding theory* (see Clark and Paivio 1991) proposes that there are two distinct working memory systems: the visuospatial system deals mostly with visualizations and the verbal system deals mostly with texts and narrations (see also Castro-Alonso and Atit this volume, Chap. 2). Notably, dual coding theory argues that these systems are interconnected, and fostering these associations produce more effective learning. In this case, combining visualizations and text makes it easier to process and memorize information than purely providing visualizations or text alone. This effect has been termed the *multimedia principle* (e.g., Mayer 1989; see Butcher 2014), in that two different modes are better than one.

Particularly for science learning, the combinations of visuospatial and verbal representations can help learners understand more effectively complex *cause and effect* systems. For example, visualizations can be scaffolds to avoid misinterpretations that could happen when learning science systems from verbal information only (e.g., Eitel et al. 2013; see also Hegarty 2011). In more detail, Mayer and Gallini (1990) described two types of scaffolds that visualizations can convey to help learning a science system: *system topology* and *component behavior*. System topology shows the components of the system and their locations within the overall structure. Component behavior shows the changes in the components, and how these changes affect other components and the overall systemic mechanism. As the authors observed in three experiments with a total of 300 university students, both system topology and component behavior must be conveyed by visualizations to boost learning. In fact, for novice learners studying brakes, pumps, and electric generator systems, it was observed that when only one of these scaffolding functions was provided, the outcomes for conceptual recall and problem solving were equivalent to not providing visualizations. Hence, both scaffolds explaining the topology and the behaviors were required to produce significant gains for visualizations compared to text-only information.

Altogether, these findings support the argument that visualizations can be useful assets for learning about health and natural sciences. However, as observed by Vekiri (2002), for visualizations to be effective, they must help to process the textual learning material. For example, by scaffolding the verbal information, visualizations can aid in processing the learning content. On the contrary, visualizations not designed for this scaffolding purpose can be ineffective or even counterproductive for learning. How to design instructional visualizations, in order to facilitate visuospatial processing and thus optimize science learning, can be informed by cognitive load theory, as described next.

5.2 Cognitive Load Theory

Cognitive load theory (see Sweller et al. 2011; see also Sweller et al. 2019) is an instructional theory based on the knowledge of the human cognitive architecture. The theory, broad enough to include many learning situations, has dealt with visual, spatial, verbal, and auditory learning materials on a number of diverse topics. However, in this chapter, we will focus on visuospatial materials about health and natural sciences. As outlined below, there are different examples of cognitive load theory being applied to instructional visualizations about the health sciences (see Issa et al. 2011; Wilson 2015; see also Fraser et al. 2015) and the natural sciences (see Ginns 2005; Schneider et al. 2018).

5.2.1 Science as a Relevant Category of Knowledge

There are many ways of categorizing knowledge with most schemes having limited or no instructional consequences. One scheme that has profound instructional consequences was provided by David Geary (Geary and Berch 2016; Sweller 2016). Geary divided knowledge into biologically (or evolutionary) primary and secondary knowledge. He argued that humans have evolved to acquire various forms of primary knowledge, such as learning to speak a native language, or recognizing gestures (see Castro-Alonso et al. this volume-b, Chap. 7). Generic-cognitive skills, such as general problem-solving skills, also provide a large class of biologically primary skills (Tricot and Sweller 2014). It is argued that we have evolved to acquire these skills naturally and therefore they are learned easily, automatically and without instruction.

Unlike biologically primary knowledge, we have not evolved to acquire specific biologically secondary knowledge. We can acquire secondary knowledge but do so consciously, with effort, and often assisted by explicit instruction (Geary 2002, 2007). Almost everything that is taught in training and education institutions is biologically secondary (Sweller 2015). We invented these institutions because, without them, the cultural knowledge that constitutes secondary skills tends not to be acquired (Geary 2002, 2007). Learning to read and write provides an obvious example of secondary knowledge, and in direct contrast to learning to listen, speak, and gesture (primary knowledge).

While generic-cognitive skills commonly provide examples of primary knowledge, domain-specific skills commonly provide examples of secondary skills. For example, the educational syllabi for the health and natural sciences are composed mostly of secondary skills. Learning science concepts and skills needs to be taught explicitly because they are domain-specific skills that we have not evolved to acquire automatically (Tricot and Sweller 2014). In contrast, learning a general problem-solving skill such as using mean-ends analysis (cf. Larkin et al. 1980) to solve a wide variety of problems cannot be taught because it is learned automatically as a biologically primary skill (unless specific applications are guided; see Youssef et al. 2012). Cognitive load theory is primarily concerned with the acquisition of biologically secondary rather than primary knowledge. Consequently, the theory is highly relevant for science instruction, including the use of instructional visualizations. The theory is described next.

5.2.2 Human Cognitive Architecture

As stated above, cognitive load theory mainly describes the acquisition of biologically secondary knowledge. It only is concerned with primary knowledge to the extent that primary knowledge can assist in the acquisition of secondary knowledge (Paas and Sweller 2012). The cognitive architecture used to acquire secondary knowledge and skills mimics the procedures used by biological evolution (see Sweller and Sweller 2006). It can be described by the following five basic principles of cognitive load theory, outlined by Sweller and Sweller (2006):

- *The information store principle.* In order to function, human cognitive architecture requires a substantial store of information. Long-term memory provides that large store. For example, visual long-term memory has shown a significant capacity to store details about pictures of objects (e.g., Brady et al. 2008). A major purpose of instruction is to assist learners in acquiring this large long-term store of biologically secondary, domain-specific information. In consequence, a chief purpose of science education is to assists learners to acquire scientific information to incorporate to long-term memory.
- *The borrowing and reorganizing principle.* Most biologically secondary information held in long-term memory is obtained from other people, by listening to what others tell us, watching what they do, or observing what they show. Our ability to communicate information between us is a biologically primary skill that we have evolved to acquire. Accordingly, communication between us provides the primary means by which we obtain the substantial amounts of secondary information held in long-term memory. For example, we have incorporated information from teachers and instructional visualizations to enhance our knowledge of health and natural sciences.
- *The randomness as genesis principle.* Sometimes, we are required to generate novel information. As it is new information, no one else has it, so it cannot be obtained from others. Under those circumstances, information can be generated during problem-solving by using a generate-and-test procedure. We can randomly generate novel information and test it for effectiveness with effective information retained and ineffective information discarded. These processes take place in working memory, and if they involve visualizations, they occur in the visuospatial processor of working memory (and the central executive, see Castro-Alonso and Atit this volume, Chap. 2).
- *The narrow limits of change principle.* Only limited amounts of novel verbal or visuospatial information can be processed at any given time. Working memory is used to manage novel information and working memory is severely restricted in both capacity and duration when processing novel information (see Cowan 2001). Furthermore, it is subject to additional depletion after use (and recovery after rest, see Chen et al. 2018). When investigating the limits of visuospatial processing in working memory, Luck and Vogel (1997) reported that approximately four features could be processed correctly when memorizing displays of squares that changed in color, orientation, and size. More recently, Oberauer and Eichenberger (2013) replicated these findings and showed that there is a trade-off in visuospatial processing between the number of visual elements, number of features, and detail precision. These studies show that working memory processing is severely limited when dealing with novel visuospatial information, which can include science visualizations.

- *The environmental organizing and linking principle.* Once information is stored in long-term memory, it can be transferred to working memory following environmental signals to generate action appropriate to the environment. Information transferred from long-term to working memory has none of the limitations affecting novel information. There are no known capacity or duration limitations when working memory processes familiar information transferred from long-term to working memory. It is at that point that the full advantages of education manifest themselves. For example, although novice students may struggle when processing one visual representation of molecules, more knowledgeable learners can process several representations simultaneously (cf. Stull et al. 2018), showing that chemistry education can overcome initial visuospatial processing limitations.

Cognitive load theory uses the cognitive architecture described by these five principles to devise effective instructional procedures (see Paas and Sweller 2014). Those procedures are based on the assumptions that learners must acquire biologically secondary, domain-specific knowledge stored in long-term memory for use in an appropriate environment. This general goal of cognitive load theory includes the specific learning scenario of studying science topics through visualizations, as described next.

5.3 Cognitive Load Theory Effects for Science Visualizations

University students from the areas of health and natural sciences must acquire biologically secondary scientific knowledge to succeed in their fields. Cognitive load theory can be employed to produce more effective instructional visualizations for science learning. In order to do this, the limits of visuospatial processing in working memory must be considered and circumvented (cf. Castro-Alonso and Uttal this volume, Chap. 3).

There are basically two tracks to elude the limitations of visuospatial processing: (a) *reducing unnecessary* visuospatial processing, and (b) *increasing total* visuospatial processing. As predicted by cognitive load theory, following one or both of these tracks will lead to more effective instructional visualization. In the remainder of the chapter, we will describe five methods that follow these paths. Cognitive load theory describes them as *effects* (see Sweller et al. 2011). A related theory, the *cognitive theory of multimedia learning*, describes them as *principles* (see Mayer 2014a). These methods to optimize science visualizations and their names in both theories are shown in Table 5.1.

A further description of the cognitive load theory effects in these examples is provided next, where we describe the five effects and also consider the influence of visuospatial processing. Details of most of the visuospatial processing abilities and instruments described in this chapter can be found in Castro-Alonso and Atit (this

Table 5.1 Methods to optimize visualizations and examples for visuospatial information

Cognitive load theory	Cognitive theory of multimedia learning	Example of solution
Split attention effect	Spatial contiguity principle	Physically integrate the visuospatial information
Modality effect	Modality principle	Present some information auditorily
Redundancy effect	Coherence principle	Delete unimportant visuospatial information
	Signaling principle	Signal important visuospatial information
Transient information effect		Avoid fast-paced visuospatial information

volume, Chap. 2), and also other versions of similar tests are described in Castro-Alonso et al. (this volume-a, Chap. 8) and in Castro-Alonso et al. (2018a).

5.4 Split-Attention Effect and Spatial Contiguity Principle

According to cognitive load theory, a *split-attention effect* occurs when a multimedia presentation is designed in such an ineffective manner that the visuospatial contents are separated in the display, so learners have to mentally integrate them in working memory (see Ayres and Sweller 2014; see also Fraser et al. 2015).

For example, an instructional page of human anatomy could depict the skeletal system of the hand as shown in Fig. 5.1a. As the bones are exhibited at the top left and the explanatory legend is shown at the bottom right, this design would require students to look up and down continuously and would produce a split-attention effect, counterproductive to learning. A solution would be to move the texts from the legend into closer proximity to the bones, as shown in Fig. 5.1b. This physical integration would increase *spatial contiguity* between text and images. Such an integrated format would require less visuospatial processing due to searching and matching, and thus be more useful for learning, as it has been shown since the seminal study of this effect (Tarmizi and Sweller 1988) and many others which followed (e.g., Chandler and Sweller 1991; Makransky et al. 2019; Purnell et al. 1991).

The meta-analysis by Ginns (2006), which considered a total of 37 effect sizes for the spatial contiguity principle, showed an overall effect size of $d = 0.72$. A more current meta-analysis by Schroeder and Cenkci (2018) included additional 21 independent comparisons. In total, it analyzed 58 independent effect sizes (n = 2,426 participants), the majority (60%) concerning post-secondary education. The overall effect size of this updated meta-analysis was of g = 0.63. According to the benchmarks of effect sizes by Cohen (1988), these overall magnitudes represents medium to large sizes. Next, we give examples for health and natural sciences visualizations being optimized when considering this effect.

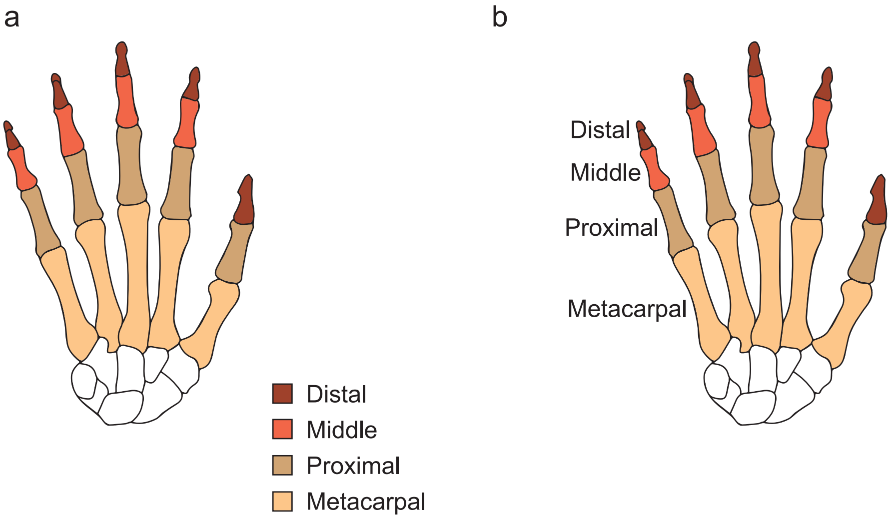


Fig. 5.1 Example of (**a**) separated format that produces split attention, and (**b**) integrated format that follows the spatial contiguity principle

5.4.1 The Effect in Optimization of Science Visualizations

The meta-analysis by Schroeder and Cenkci (2018) described above, also analyzed the split-attention effect in different disciplines. For anatomy/medicine, 8 comparisons ($n = 368$) showed an overall effect size of $g = 0.52$. For biology/earth science, 12 effect sizes ($n = 557$) showed an overall $g = 0.56$. These effects correspond to medium sizes.

An example of university biology study showing the split attention effect is given by Cierniak et al. (2009), in which the learning topic was the structure and function of the kidney's unit, known as the nephron. The authors compared learning of 98 university students (64% females) randomly allocated to either a split or an integrated format between nephron diagrams and textual labels. Students were assessed in both simple tests (terminology and labeling), and more demanding tasks (complex facts and inferences). It was observed that the spatial contiguity condition outperformed the split-attention condition in three out of the four measures, as there were no significant differences in the complex inference tasks.

Similar results were obtained by Erhel and Jamet (2006) with multimedia modules showing the topics of the human heart and the replication of a virus. In the experiment with 72 psychology undergraduates (85% females), the participants were randomly assigned to one of three conditions: (a) *separated*, where the images and the blocks of texts were spaced apart on the screen; (b) *integrated*, where the images and the blocks of texts were near to each other, thus following the spatial contiguity principle; and (c) *pop-up texts*, where the images and texts also followed the spatial contiguity principle, but in this case an interaction was required from the learners (see also Castro-Alonso and Fiorella this volume, Chap. 6). For the four assessed measures (two retention and two transfer tests) it was observed that the integrated and pop-up texts conditions outperformed the separated design.

Huff et al. (2012) presented a stereoscopic vexing-image technology to manage split-attention, in an experiment with 80 university students (80% females). The task was to notice failures when contrasting two visualizations of mechanical pendulum clocks. Randomly, a group of split design was compared to a group with this novel technology that avoids eye movement. As predicted, the stereoscopic technology, due to avoiding split-attention, produced a faster and more accurate learning performance. Next, we describe how the split-attention effect and spatial contiguity principle are influenced by high versus low visuospatial processing.

5.4.2 *Visuospatial Processing Influencing the Effect*

Wiegmann et al. (1992, Experiment 2) investigated 34 psychology undergraduates learning about the human autonomic nervous system from concept maps. Randomly, the participants were allocated to one of two map design conditions: (a) an integrated format showing a single large map, or (b) a split attention format where six interconnected smaller maps showed the information. Also, the visuospatial ability of field independence was measured with the Group Embedded Figures Test (see discussion of these abilities and test in Castro-Alonso and Atit this volume, Chap. 2). Results showed that, for the students with higher field independence, the split attention design was more effective for learning than the integrated format. In contrast, those with lower scores in the visuospatial processing task were not benefitted by either design. Similarly, Fenesi et al. (2016, Experiment 1) used a dual working memory task to measure working memory capacity of 76 undergraduates (59% females) required to learn the topic of visual memory from slideshows. According to the design of each slide, the participants were randomly allocated to a split attention or an integrated condition. Linear regression analyses showed that working memory capacity predicted learning for the split attention group but not for the integrated condition.

Huff and Schwan (2011) measured three-dimensional (3D) mental rotation of 84 university students (68% females), employing the common instrument called the Mental Rotations Test. In the study, the learning task involved relating structural information from proteins shown in different animations. For this biochemistry task, results showed that high mental rotators outperformed low mental rotators when the different animations were presented in a split attention format. However, in the integrated presentation, where the animations followed the spatial contiguity principle, mental rotation scores did not influence achievement.

Bauhoff et al. (2012) investigated 44 university students (50% females) attempting to notice missing pieces and other failures in two comparable visualizations of mechanical pendulum clocks. Different degrees of split attention designs were investigated by changing the distance between both clock visualizations. The participants were also assessed on visual working memory with the Visual Patterns Test. Results showed a split attention effect, as more separated visualizations involved longer processing intervals. In addition, participants with lower visual working memory had to rely on their knowledge of the clock's mechanisms to cope with the demanding split attention formats.

Using a more abstract task, Dutke and Rinck (2006) studied 96 university participants (61% females) memorizing arrangements of either two or five images of tools, musical instrument, and animals. They also measured the students' scores in a dual visuospatial task of working memory. Results showed that students with lower dual visuospatial scores could not memorize the arrangements with five images as efficiently as that with only two pictures. In other words, the split attention with five different depictions was not as manageable as the split attention with two depictions. In contrast, high visuospatial students could manage both arrangements of five and two images efficiently. In conclusion, and consistent with the predictions of the split attention effect and the spatial contiguity principle, separated formats tend to be counterproductive to learning for students with less visuospatial processing capacity. In contrast, the split attention formats are not as problematic for students with greater visuospatial resources or abilities, who are more capable of coping with these demanding visualization designs.

5.5 Modality Effect or Modality Principle

A *modality effect* (e.g., Mousavi et al. 1995) is observed when instructional visualizations are less effective when supplemented with written text as compared to spoken text (see Fraser et al. 2015). In a meta-analysis of 43 effect sizes and more than 1900 students, Ginns (2005) concluded that this principle presented a medium to large effect size for instruction ($d = 0.72$). Moreover, when analyzed by instructional discipline, the meta-analysis revealed a large effect for science topics ($d = 1.20$).

We consider two non-mutually exclusive explanations for this effect or principle. The first explanation, described in Low and Sweller (2014) and consistent with the cognitive theory of multimedia learning (see Mayer 2014b), is based on certain separability when processing visuospatial and auditory information (see also Castro-Alonso and Atit this volume, Chap. 2). As reviewed by Penney (1989), this separability can be observed in experiments showing *double dissociations*, in which: (a) visuospatial information is selectively interfered by new visuospatial information, but not as much by new verbal information, and (b) verbal information is selectively interfered with by new verbal information, but not as much by new visuospatial information (e.g., Brünken et al. 2002, Experiment 1).

The modality principle calls to employ this degree of separability to increase the total working memory capacity allocated to learning. For instance, when learners study visualizations, visuospatial working memory processing is devoted to the visual learning elements. In the example of Fig. 5.2, visuospatial processing

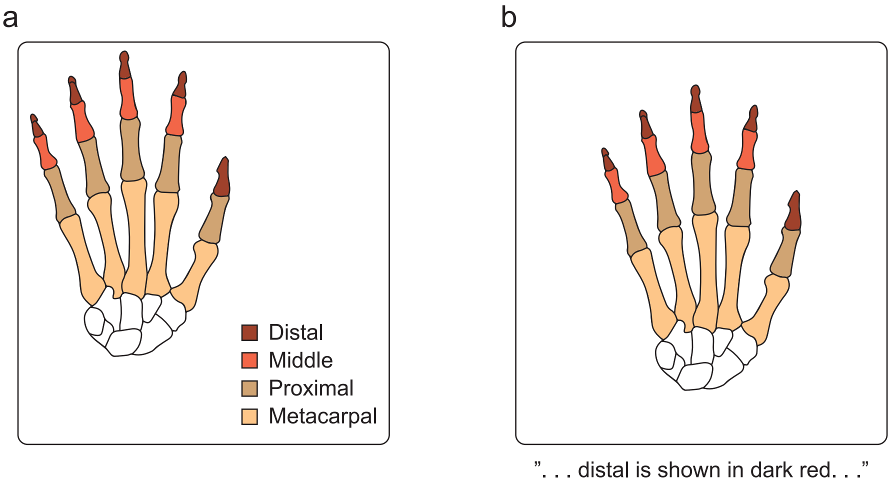


Fig. 5.2 Example of (**a**) separated format that produces split attention, and (**b**) format with some of the information in auditory working memory, fostering a modality effect or modality principle

resources will be employed in studying the anatomical relationship between the bones of the hand. If the names of the bones are written, then extra visuospatial processing would be required for reading those names and matching them to the bones. Thus, cognitive load would be added to the visuospatial processor of working memory. This can be particularly problematic if the written information is far from the depicted learning information, generating split attention between the learning elements and their names (see Fig. 5.2a). In contrast, if the names of the bones are spoken, this narration can be processed somewhat separately, and thus visuospatial processing is not overloaded, and a possible split attention does not occur (see Fig. 5.2b).

A second explanation can also be provided for this effect. As noted in Sect. 5.2.1 (see also Ong 1982; Paas and Sweller 2012), since listening to spoken texts is a biologically primary knowledge, it can involve less working memory processing than the biologically secondary knowledge of reading written texts. Examples of the research about modality effects on science education are described next.

5.5.1 *The Effect in Optimization of Science Visualizations*

We provide four examples of experiments showing a modality effect for instructional visualizations about science or technical topics. First, Kühl et al. (2011) investigated 80 university students (79% females) learning the biology topic of fish locomotion from computer presentations. Results showed that narrated multimedia outperformed written multimedia in both retention and transfer tests. Second, the study by Moreno and Mayer (1999, Experiment 1) concerned 132 university students learning the topic of lightning formation from different designs of dynamic visualizations. When comparing the animations supplemented with spoken versus written texts, it was observed that the spoken format presented significantly higher scores on tests of retention and transfer. Similarly, Schmidt-Weigand et al. (2010, Experiment 1) investigated 90 university students (58% females) learning lightning formation from visualizations and found that the participants studying with supplementary auditory explanations outperformed those presented with supplementary on-screen texts. Last, Kalyuga et al. (1999, Experiment 1) assessed first-year trade apprentices learning to interpret a fusion diagram for soldering. After randomly allocating a group to a diagram supplemented with written texts versus a group given the diagram and auditory texts, it was observed that the narrated condition self-rated less cognitive load and obtained higher performance scores in this engineering task.

The modality effect or modality principle can also be influenced by the students' visuospatial processing ability. Although this influence has not often been directly investigated for this effect, the following two examples provide some evidence.

5.5.2 Visuospatial Processing Influencing the Effect

In Experiment 2 reported in Seufert et al. (2009), 78 university students (74% females) were presented computer static pictures and texts about the structure and function of the enzyme ATP Synthase. For this biology topic, half of the participants received on-screen texts and the other half was given the textual information as narrations. Also, an aggregated score of visuospatial processing was calculated by averaging the scores in two common tests: the 2D mental rotation instrument termed the Card Rotations Test, and the mental folding instrument called the Paper Folding Test (see Castro-Alonso and Atit this volume, Chap. 2). Learning was measured with recall, comprehension, and transfer tests. Results showed a modality trend for the three tests, being only significant for recall performance. Hence, recalling facts about the enzyme was better when the static visualizations included narrated rather than on-screen texts. It was also observed that visuospatial processing was a significant predictor in comprehension and transfer performance. In other words, for visualizations supplemented with either narrated or visual texts, higher visuospatial processing was beneficial for comprehension and transfer achievements. In short, although a modality effect was observed, and visuospatial processing abilities were influential, there were no interactions between the format of the texts and visuospatial processing of the students.

Similarly, Lee and Shin (2012) investigated 72 adult participants attempting the procedural task of replacing a printer cartridge. In the study, visuospatial processing of the participants was measured by aggregating the scores of the 3D mental rotation Cube Comparisons Test and the mental folding Paper Folding Test. With the combined scores, a median split separated high vs. low visuospatial processing participants. For task performance, comparisons were made between high and low visuospatial subjects, given either written or auditory instructions for the procedures. For the tasks shown as static images, findings showed that high visuospatial participants performed significantly better than lower spatial scorers. In contrast to this visuospatial processing effect, there were no differences in attempting the task after reading or hearing the instructions. In other words, no modality effect was observed, but only that visuospatial processing was beneficial to learn from both written and auditory supplementary texts.

Although the two examples of this section investigated the effects of visuospatial processing on the modality effect, they did not show interactions where a low versus a high degree of visuospatial processing would affect differently studying science visualizations supplemented with either written or spoken texts. In other words, there is a research gap in studies investigating the effects of visuospatial processing on the modality effect or principle.

5.6 Redundancy Effect and Coherence Principle

The *redundancy effect* (see Kalyuga and Sweller 2014; see also Fraser et al. 2015) is observed when there is more than the essential visuospatial information provided to learn, so students have to process both essential and non-essential information, leading to a greater reduction of visuospatial working memory available for learning. For the same anatomy example (see Fig. 5.3a), if the texts of the bones are already integrated into the anatomy images, having a legend at the bottom right would be unnecessary, and it might produce a redundancy effect. To optimize

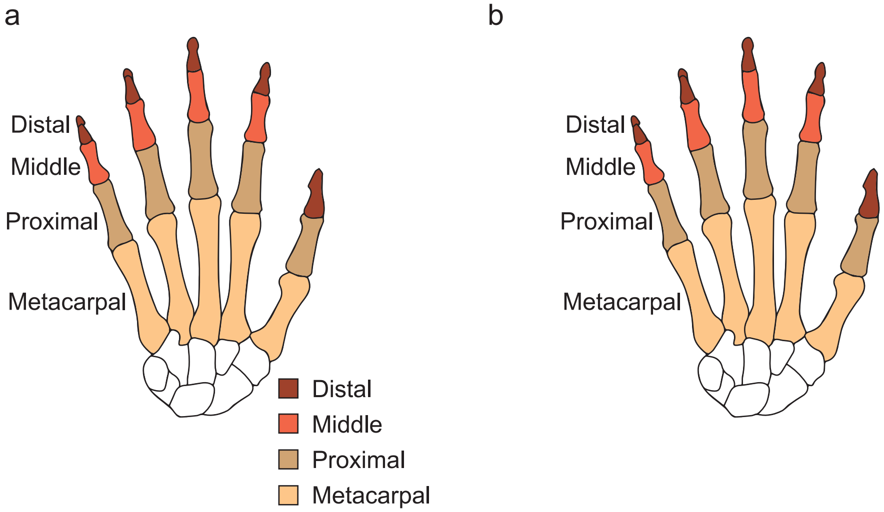


Fig. 5.3 Example of (**a**) redundant format, and (**b**) non-redundant format that follows the coherence principle

learning, deleting the legend would be preferable, in a design that follows the coherence principle (see Fig. 5.3b), and also the spatial contiguity principle.

In a meta-analysis about redundant information, Rey (2012) collected 34 effect sizes ($N = 3{,}535$ participants) for retention tests, and 21 effect sizes (1,634 participants) for transfer tests. The analyses showed an overall small to medium effect size for retention measures ($d = 0.30$) and an overall medium effect size for transfer assessments ($d = 0.48$). Examples related more exclusively to visualizations depicting health and natural sciences are described next.

5.6.1 The Effect in Optimization of Science Visualizations

In a study with 49 first-year medicine students (33% females), Garg et al. (1999) compared the instructional effectiveness of virtual visualizations showing either few or multiple rotational views of carpal bones. As there was no significant difference between both views, the visualization with more images was not more productive than that with fewer images for learning these anatomy structures, suggesting redundancy. For the natural science topic of electrical light circuits, Chandler and Sweller (1991, Experiment 2) provided the first evidence for the redundancy effect in cognitive load theory. In the study with 28 trade apprentices, two redundant conditions were tested: a split attention or separated condition (the diagram far from the redundant texts) was compared to an integrated condition (the diagram near redundant texts). It was observed that both conditions did not differ in learning outcomes. The authors concluded that, as opposed to integrated formats with only relevant information (presented in Sect. 5.4), integrated formats with redundant information were not useful learning tools.

In the related area of meteorology, in an experiment with 74 university participants studying the topic of lightning formation, Harp and Mayer (1997) compared the instructional effectiveness of booklets with or without redundant information that was also seductive. The between-subjects study investigated four groups, according to a 2 (Seductive texts: Yes vs. no) × 2 (Seductive illustrations: Yes vs. no) design. It was observed that the best learning condition was that with no extra seductive adjuncts, arguably because this seductive information distracts from the relevant passages and illustrations to understand the chain of events in lightning. In a later study of four experiments, totaling 357 undergraduates studying the formation of lightning, Harp and Mayer (1998) consistently observed that extra information (texts and visualizations) hindered performance on retention and transfer tests (see also Eitel et al. 2019).

Investigating this effect further, Mayer et al. (2008) reported two experiments studying the influence of level of interestingness in redundant texts. The novelty of this approach is that all conditions included off-topic texts of comparable lengths, but these redundant texts had been rated before as highly interesting vs. highly uninteresting. In Experiment 1, with 89 psychology undergraduates (66% females), the learning task was understanding how the cold virus infected the human body.

Randomly, half of the participants learned this health sciences lesson including *low interestingness* redundant texts, and the other half studied under the *high interestingness* condition. It was observed that the low interestingness outperformed the high interestingness (seductive) groups in the transfer tests.

Experiment 2, with 53 psychology undergraduates (75% females), extended these findings to slideshow presentations about the process of swallowing during digestion. As both low and high interestingness texts were matched in the quantity of redundant information, both experiments showed that more interesting irrelevant supplements (seductive) could be more damaging for understanding the main learning concepts than less interesting redundant additions. The influence of visuospatial processing on the redundancy effect and the coherence principle is described next.

5.6.2 Visuospatial Processing Influencing the Effect

In the experiment by Levinson et al. (2007), 118 psychology undergraduates (75% females) were randomly assigned to multimedia showing either key views or multiple views of the brain. In the key views conditions, only four images were shown (anterior, inferior, lateral, and superior views of the brain photographed digitally). In contrast, the multiple views groups studied 24 images (digital photographs at 30° increments around the brain model). A redundancy effect was observed, as the multiple views were significantly less effective instructional visualizations than the key views. Hence, employing visually demanding anatomical depictions, this study provided a replication to the findings (see above) by Garg et al. (1999) with simpler carpal bone images. In addition, the study by Levinson et al. (2007) also measured student's performance on the 3D instrument Mental Rotations Test. Notably, it was observed that the disadvantages of the multiple views were larger for students with lower mental rotation. As such, for low visuospatial processing students, performance after multiple view study was approximately 30% lower than outcomes after studying the key views.

Korbach et al. (2016) investigated 108 university students (74% females) learning about the structure and function of the enzyme ATP Synthase from 11 multimedia slides showing images and texts. Randomly, the students were allocated to a group without redundant information versus a group with redundant information in 4 of the 11 screens. Visuospatial processing was also assessed by averaging the scores of two paper instruments, respectively measuring 2D mental rotation and mental folding. As predicted, an overall redundancy effect was observed, in which the redundant condition was outperformed in retention and comprehension tests by the non-redundant (coherence) design. Also, the effect was more significant for low visuospatial processing students.

Not only the visuospatial processing of working memory but also total working memory can influence the redundancy effect. For example, Fenesi et al. (2016, Experiment 2) measured the working memory capacity of 71 undergraduates (63% females), employing a dual instrument that involved a memory and a processing task. Then, participants were shown slideshows depicting the topic of visual memory. Randomly, the participants observed these slideshows in either a redundant or an essential design for each slide. Linear regression analyses showed that working memory capacity predicted learning for the redundant condition but not for the essential group. Consistent with the prediction of cognitive load theory, the redundant design hindered learning in those students with lower working memory capacity, but it was manageable by those with more cognitive resources. Although the working memory test used in this experiment was not exclusively visuospatial, the results show that total working memory (including verbal working memory) helps to process redundant information such as non-essential illustrations.

In conclusion, as predicted by cognitive load theory and the cognitive theory of multimedia learning, redundant visualizations hinder learning because they require unnecessary processing in understanding the main science concepts. Redundant visuospatial information is less problematic for high visuospatial processing students, as they can manage in working memory both essential and redundant information. In contrast, low visuospatial processing students are less able to process both essential and non-essential or redundant visuospatial information.

5.7 Signaling Principle

The *signaling principle* (see van Gog 2014) incorporates visual cues to signal the essential learning elements and their relationships, so learners know where their main focus should be. We found three meta-analyses for the signaling principle. The most recent of these analyses were conducted by Schneider et al. (2018) on 145 comparisons (from 103 studies and $N = 12{,}201$ participants). The analysis showed a positive effect of signaling for retention scores, as 117 out of 139 comparisons revealed beneficial signaling representing an overall medium effect size ($g = 0.53$). Transfer performance showed that 55 out of 70 comparisons were positive for signaling, in an overall small to medium effect size ($g = 0.33$). For cognitive load, 19 out of 27 effect sizes were positive and showing an overall small size ($g = 0.25$), indicative that signaling reduced perceived cognitive load on learners. Also, 20 out of 27 comparisons were negative for learning time, representing an overall small to medium size ($g = -0.30$), which denoted that materials with signals involved more learning time. The study by Xie et al. (2017) included three meta-analyses: (a) for retention scores, the meta-analysis of 25 studies ($N = 2{,}910$) revealed a small to medium effect ($d = 0.27$); (b) for transfer scores, the meta-analysis of 29 studies ($N = 3{,}204$) revealed a small to medium effect ($d = 0.34$); and (c) for lowering perceived cognitive load, the meta-analysis of 32 studies ($N = 3{,}597$) revealed a small effect ($d = 0.11$). The third analysis, conducted by Richter et al. (2016), reported that 38 out of 45 comparisons (from 27 studies) showed positive effects for signaling, and that this represented a small to medium overall effect size ($r = .17$). These meta-analyses, which included some common sources, supported the effectiveness of the signaling principle in increasing retention and transfer scores, while lowering perceived cognitive load. These positive effects of visual signaling are also observed for topics in health and natural sciences, as described next.

5.7.1 The Effect in Optimization of Science Visualizations

Based on the review by de Koning et al. (2009), signaling can aid learning from visualizations by highlighting (a) *importance* and (b) *relationships*. The first goal of highlighting importance is the most common. It signals the main learning elements. As redundant or non-essential information is given less precedence, signaling produces less cognitive load that could impede learning. The second goal of highlighting relationships has been less researched. It involves showing relations between the learning elements, which makes it easier to group and memorize them together.

To attain both goals, signaling techniques can be broadly organized in two groups, as described in Castro-Alonso et al. (2014a; see also de Koning et al. 2009): (a) signaling *with* added elements, and (b) signaling *without* added elements. Signaling with extra elements include pointing devices (e.g., arrows, fingers, hands, and lines), frames, alphanumeric characters, labels, among others. Signaling without these elements comprise blurring, lighting, transparencies, flashing, zooming, colors, contrasts, and combinations. An example of these two types of signaling techniques is provided in Fig. 5.4, which shows a hydrogen bond between water molecules depicted without signaling (Fig 5.4a), using signaling with added elements (Fig 5.4b), and using signaling without added elements (Fig 5.4c).

An example of effective signaling with added elements, in this case, the added depiction of red arrows, is provided by Lin and Atkinson (2011). A group of undergraduates given static images with signaling was faster in learning the rock cycle topics than the group given static images without signaling. It was observed that this positive effect for signaling on static images of the rock cycle was not presented on equivalent animations. Hence, consistent with many other domains, an important variable to consider in signaling studies is whether the visualization is static or animated.

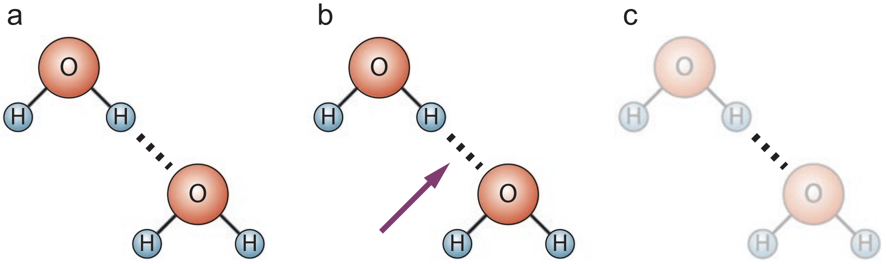


Fig. 5.4 Hydrogen bond between two molecules of water. Example of (**a**) no signaling, (**b**) signaling with added elements (arrow), and (**c**) signaling without added elements (transparency)

In contrast, we provide three examples showing effective signaling without added elements. *Color coding* was used by Skulmowski and Rey (2018) on an anatomy task. In the experiment, 108 adults (78% females) had to memorize the parts of a fictional 3D bone model. Following a 2 Realism (high vs. low) × 2 Signaling (colors vs. no signaling) between-subjects design, four groups were compared. Showing an interaction, color signaling was only helpful with the high realistic depiction of the bone model but was counterproductive on the depiction with fewer details. In other words, when more visuospatial processing was required due to redundant (unnecessary) realistic details, signaling was a needed asset to reduce this cognitive load and produce better memorization of the anatomical parts.

Amadieu et al. (2011) conducted an experiment employing *zoom-in* to focus on the main elements of a neurobiology phenomenon related to synapsis. The study investigated 36 psychology undergraduates (83% females) learning from an animation with or without this signaling technique. It was observed that only the signaled animation with zooms helped to increase the comprehension scores when watching more than once the dynamic visualization. This means that even repeating the animation was not helpful in the conditions without signaling.

The technique of *spotlight cueing* is reported by de Koning et al. (2010) in an experiment with 76 psychology undergraduates (74% females) studying animations of the human cardiovascular system. A non-signaled condition was compared to a signaled condition where the main elements kept their luminance, and the less important visuals were obscured. When comparing both conditions, it was observed that the spotlights were effective for retention, inference, and transfer outcomes.

Although there are examples of successful signaling with added elements, such as the mentioned study with red arrow signals (Lin and Atkinson 2011), it was suggested by de Koning et al. (2009) that this type of signaling could be less effective than that without added elements. This is because not adding elements could be more effective, as it keeps constant (and ideally low) the number of visuospatial elements to process. The influence of visuospatial processing on signaling is described next.

5.7.2 Visuospatial Processing Influencing the Effect

Münzer et al. (2009) investigated 94 university participants (77% females) studying a multimedia module about the biological topic of synthesis and structure of the ATP molecule. A non-signaled static pictures condition was compared to a signaled static pictures format that included motion arrows. Also, a global score of visuospatial processing was calculated by averaging the scores of the Card Rotations Test of mental rotation and the Paper Folding Test of mental folding. Results showed that visuospatial processing was a significant predictor of learning with the signaled format but not with the non-signaled depictions. Thus, in the signaled condition, visuospatial processing may have helped to deal with the extra information of the arrows, and this information was used to achieve better learning. In contrast, low visuospatial processing students could not cope with both the visualizations and the extra information of the arrows and were not benefited by these extra signals. With the non-signaled statics, both low and high visuospatial processing showed similar low performance, as there were no cues to produce positive signaling effects.

Imhof et al. (2013) investigated 71 university students (65% females) learning about fish locomotion patterns from three types of computer static visualizations, either presenting or not presenting static arrows signaling the fish motions. Also, mental rotation with 3D figures and mental folding were measured with the Mental Rotations Test and the Paper Folding Test, respectively. Results showed that adding signaling arrows to multiple visualizations was less effective than adding the arrows to a single visualization. In other words, the multiple visualizations already presented useful information of the fish movements, so adding a signaling with added elements was redundant and harmful for learning. Also, mental rotation and mental folding did not interact with the signaling effects. Presenting higher visuospatial processing scores predicted higher achievements in all conditions, independent of the type of signaling and visualization.

Lee and Shin (2011) reported similar findings in their study with 63 adult participants (44% females) learning about the four-stroke internal combustion engine. The participants were randomly allocated to one of three instructional visualization conditions: (a) static pictures, (b) static pictures signaled with the extra element of motion arrows, and (c) animations. Also, a composite visuospatial processing score was calculated with the results of a 3D mental rotation test (the Cube Comparisons Test) and a mental folding instrument (the Paper Folding Test). The aggregated score was used for a median split to compare high vs. low visuospatial students. It was observed that higher visuospatial processing students outperformed their lower counterparts in all three types of visualizations, including signaling or non-signaling static picture conditions. In other words, including arrows to signal the relevant movements in the engine system was not helpful for low visuospatial processing students, because they performed poorly in both signaling or non-signaling static picture conditions, significantly lower than the high visuospatial processing participants. These examples suggest that visuospatial processing may be more influential than signaling with added elements to boost learning from science visualizations.

5.8 Transient Information Effect

Our last effect based on cognitive load theory is the *transient information effect* (see Ayres and Paas 2007b). This occurs when videos or animations show information that leaves the screen too rapidly for learners to cope with the pace and process it in visuospatial working memory. The effect predicts that highly transient information will be less effective for learning than less transient information (e.g., Castro-Alonso et al. 2014b, 2018b). A similar negative impact of long narrations has also been investigated (e.g., Singh et al. 2012; Wong et al. 2012).

Castro-Alonso et al. (2014a) described two general techniques to reduce the transiency of instructional visualizations: *pacing control* and *segmenting*. When following the pacing control technique, the students are given controls to adjust the pace of the animation or video, such as pause and rewind buttons (see Mayer 2008). Dynamic visualizations with features of pace control will contain less transient information and thus be more effective than visualizations where pacing cannot be controlled (see Ayres and Paas 2007a). When following the segmenting guideline, shorter animations or videos are given to students, instead of a whole dynamic visualization. By providing pauses between observations, students do not get cognitive overloaded by accumulated transient information, and consequently, these shorter segments are more efficient than a longer visualization (see Ayres and Paas 2007a).

In addition to the segmenting effectiveness due to lowering transient information, there is also another benefit of this technique: The segmenting of longer animations introduces pauses between visualizations, and these pauses can be used to include additional learning activities (e.g., answering a short question, see Cheon et al. 2014). Figure 5.5 shows the pacing control and segmenting techniques to avoid the problematic transient information in an animation.

Although both pacing control and segmenting reduce the transient information of dynamic visualizations, Castro-Alonso et al. (2014a) reported a critical difference between them (see also Spanjers et al. 2010). This difference is in the agent who segments the animation, as the *student* enacts pacing control, but the *instructional designer* produces segmenting. As such, segmenting could be more effective than pacing control because it is an expert instructional designer who chooses to add pauses in the best places for a meaningful presentation of the contents (see Spanjers

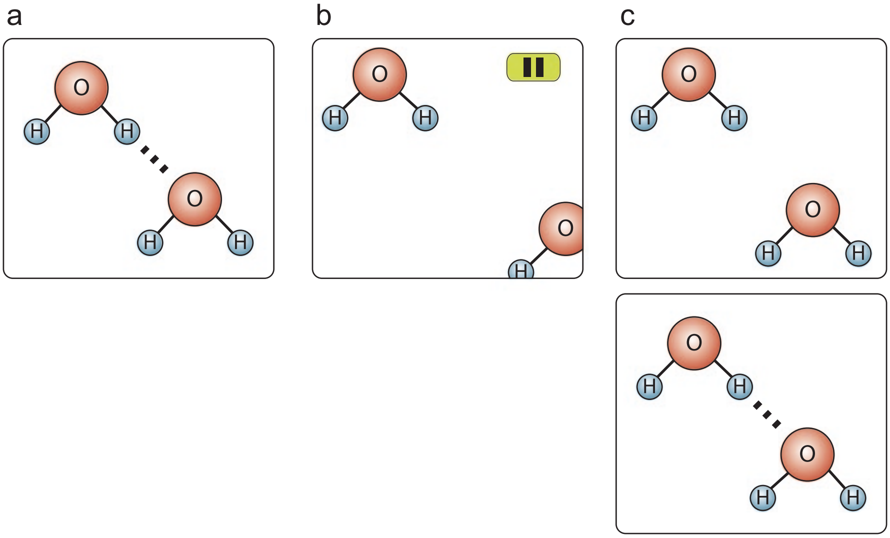


Fig. 5.5 Animations showing hydrogen bonds between molecules of water. Example of (**a**) whole transient animation, (**b**) pacing controlled animation, and (**c**) two segmented (shorter) animations

et al. 2010). In contrast, relying on novice learners to add the pauses could halt the continuity of the multimedia and lead to visualizations that are difficult to process.

Support for segmenting over pacing control is provided in the meta-analysis by Rey et al. (2019), which included results of retention and transfer tests. For the pacing control method, results revealed a non-significant effect for retention tests ($d = 0.19$), but a small to medium effect size for transfer tests ($d = 0.45$). For the segmenting technique, small to medium effect sizes were observed for both the retention ($d = 0.42$) and transfer ($d = 0.35$) tests. Hence, both techniques were effective for transfer, but only segmenting was also effective for retention assessments. Examples of these two techniques for science learning are provided next.

5.8.1 The Effect in Optimization of Science Visualizations

An example of pacing control being effective for health and natural science education is observed in Stiller et al. (2009), who reported a study of 110 university participants (76% females) studying a multimedia presentation about the structure of the human eye. Among the groups given the multimedia with explanatory on-screen texts, a pace control condition was compared to a group showing an animation without speed controls. The results revealed a higher performance of the students controlling the pace of the multimedia screens. Importantly, this effect was not observed among the groups given explanatory text as narrations, consistent with the modality effect. In other words, the pace control effect was only observed in the conditions of high visuospatial processing (learning depictions plus visual text) but not in the conditions of lower visuospatial requirements (depictions plus auditory text). Only in high processing conditions did learners need to control the pace of the multimedia in order to manage its cognitive load; in low processing conditions, learners could manage the extra load imposed by the pace of the multimedia. These findings are also consistent with the modality effect.

Another positive example of pacing control is in the study by Höffler and Schwartz (2011) with 82 university students (68% females) learning the chemical process of dirt removal from a surface. In this experiment, the groups provided with pause, rewind, and fast-forward features outperformed and self-reported less cognitive load than those without these pacing controls.

The segmenting technique has also shown effectiveness in science education. For example, Biard et al. (2018) investigated 68 occupational therapy undergraduates (87% females) learning a medical hand procedure from videos in three formats. The group assigned to the segmented videos outperformed the students in the two other groups, namely: (a) whole videos that allowed pausing, and (b) whole videos without segments. Thus, in line with the prediction by Spanjers et al. (2010) describe above, the segmented videos were more effective than longer videos, either with or without a pause feature.

Hasler et al. (2007) reported a study with 72 male primary students watching a narrated animation about the causes of day and night. A condition of a whole continuous animation was compared to a segmented format with shorter animations. For the difficult questions, it was observed that students learning from the segmented visualizations surpassed those given the continuous animations. Hence, when more working memory processing was needed to deal with difficult questions, the segmenting method was most effective.

The segmenting technique has also been employed to investigate animations vs. still pictures. In this case, the comparison is not made between longer and shorter animations, but between animations and static pictures. Visuospatial processing has also been influential in these comparisons, described next.

5.8.2 Visuospatial Processing Influencing the Effect

The transient information effect predicts that animations without pacing control will be too demanding and thus less instructionally effective than static pictures, which do not contain transient but permanent visuospatial information. Consequently, high visuospatial processing students should be better prepared to deal with transient animations, as compared to low visuospatial students, and the differences should be less manifested in static picture conditions. This prediction has been investigated for educational visualizations of both the health and natural sciences.

Regarding the health sciences, Nguyen et al. (2012) studied 60 adult participants, among university students and staff (52% females), who learned the anatomical structures of the esophagus, trachea, and mediastinal aorta. The dynamic condition studied a video of the anatomical parts continuously rotating around the axes, whereas the static condition studied six static standard views of the structures. The participants were also measured in 3D mental rotation ability using a computerized Mental Rotations Test. Results on the anatomy test showed that only in the dynamic group high visuospatial processing students outperformed their lower peers. For the statics condition, no differences were reported between high and low scorers in mental rotation.

In an experiment with 29 university students, Loftus et al. (2018) used the same visualization of the esophagus, trachea, and aorta as Nguyen et al. (2012). Loftus and colleagues also incorporated a new visualization of ankle and foot bones. Both anatomical models were shown rotating, in animations with no pacing control. A median split from the scores on the paper Mental Rotations Test was used to divide high and low visuospatial participants. Results showed that higher mental rotation students outperform their lower peers in learning tasks with these highly transient anatomical models. The largest effects favoring higher visuospatial learners were observed in tasks demanding greater mental rotations of the models.

In a study with 49 first-year kinesiology undergraduates (18% females), Berney et al. (2015) randomly allocated students to either a static or a dynamic visualization condition to learn topics about human shoulder anatomy. Also, the Mental Rotations

Test was used to measure mental rotation with 3D figures, and the Group Embedded Figures Test was employed to assess field independence. Considering the five anatomy tasks investigated, mental rotation was a broader predictor, as it predicted performance in three tasks, whereas field independence predicted performance in two tasks. This was observed for both static and animated versions.

Concerning natural science education, Aldahmash and Abraham (2009) investigated 142 students in a university organic chemistry course. The topic focused on reactions of nucleophilic substitution and elimination, and it was presented in either animations or static pictures. Before students were randomly allocated to one of these two visualization conditions, they were assessed in 3D mental rotations (the Purdue Visualization of Rotations) and field independence (the Find A Shape Puzzle). A score of total visuospatial processing was calculated by averaging the scores of both instruments. Results showed that the animated condition was more effective than the static visualizations, and that this beneficial learning effect of animation was more pronounced in students with high visuospatial processing.

In an experiment with 198 university students (76% females), Kühl et al. (2018) compared learning after watching a static picture versus an animation about the velocity of planets orbiting the sun. The animation conditions outperformed the static groups. In addition, the effect of mental folding, measured with the Paper Folding Test, was also investigated. Notably, students lower in mental folding presented lower results in the astronomy topic when they learned it from the static pictures, but presented similar results to higher mental folders with the animation. Hence, the mental folding visuospatial processing was not as necessary for dynamic visualizations as it was for statics.

In a more abstract task, Castro-Alonso et al. (2018b) investigated 104 university students (50% females) memorizing positions and colors of symbols placed on the screen. Every participant attempted the task in both a static format (symbols shown simultaneously) and a transient format (symbols shown consecutively). As predicted by the transient information effect, the outcomes were higher in the static as compared to the transient condition. Also, mental rotation with 2D shapes was measured with the Card Rotations Test and spatial working memory was measured with a computer Corsi Block Tapping Test. Multiple regression analyses showed that (a) mental rotation was a significant predictor of achievement in both the static and the transient tasks, and (b) spatial working memory was a close to significant predictor of performance in the transient but not in the static task.

Summarizing these results of health and natural sciences, we can conclude that visuospatial processing is a beneficial asset for comprehending science visualizations and multimedia. We can also draw conclusions about the prediction of the transient information effect, forecasting that visuospatial processing would be more important to deal with transient visualizations than with static pictures. The studies presented here show that this prediction needs further investigation, as both dynamic and static visualizations were supported by visuospatial abilities.

5.9 Discussion

In addition to being engaging and fun, visualizations can convey a processing advantage. For example, adequately designed instructional visualizations can help to learn from science texts, especially if the concepts are complex and need such learning scaffolds. As mentioned, visualizations need to be *properly designed* to accomplish these instructional benefits. We believe that proper instructional designs are those that follow an understanding of the human cognitive architecture applied to learning. Cognitive load theory and also the cognitive theory of multimedia learning can provide this understanding. Moreover, as these two cognitive theories investigate domain-specific biologically secondary skills, they are especially pertinent in designing visualizations for science education. In these learning situations, there are working memory limitations affecting visuospatial processing to deal with the visual and spatial information of instructional visualizations.

We considered five effects identified by these two cognitive theories, which can be applied to optimize static and dynamic instructional visualizations. These effects or principles are: (a) the split attention effect and spatial contiguity principle, (b) the modality effect, (c) the redundancy effect and coherence principle, (d) the signaling principle, and (e) the transient information effect. We presented examples for health and natural sciences instructional visualizations for each of these five methods. We also considered the role of visuospatial processing abilities, measured in standard tests that assess mental rotation, mental folding, and field independence, among others. In general, the higher the visuospatial processing ability of the learner, the greater the learning from instructional visualizations.

5.9.1 Instructional Implications for Health and Natural Sciences

A first implication for learning about the health and natural sciences is that visualizations should be designed according to cognitive principles rather than just on engagement variables. In other words, the processing advantages of instructional visualizations, such as providing scaffolds for textual information, should be utilized.

A second instructional implication is that applying the guidelines from cognitive load theory (and similar cognitive theories) can help optimize learning from science visualizations.

A third instructional implication is that measuring visuospatial processing can also help predict the most effective learning from instructional visualizations, including static and dynamic formats. The general trend is that higher visuospatial processing scores result in greater learning from instructional visualizations, but the design of the visualizations can affect this trend.

A fourth implication, concerning the split attention effect, is that visualizations should not be designed with their information separated but integrated spatially. For example, visual elements and their text labels should follow the spatial contiguity principle and be placed near each other. Also, low visuospatial processing students are particularly challenged by the separated placement of visuospatial information in visualizations.

A fifth implication, considering the modality effect, is that computer visualizations should be designed with auditory descriptions, rather than too much information on-screen. By providing narrations, the auditory processing is used and visuospatial processing is left to manage the key visual elements and not also written explanations. Narrations should be short, to avoid an adverse transient information effect.

A sixth implication concerns the redundancy effect. Extra information that is not fundamental for the learning topic should be deleted from the visualizations. This is especially important for interesting redundant supplements, as these can be more disruptive than less interesting additions. Moreover, low visuospatial processing students are particularly challenged by unnecessary visuospatial information, as it interferes more with the critical learning information.

A seventh implication, considering the signaling principle, is that visualizations could be more effective by including elements to cue the most important parts. Using signals that do not add extra visual elements, such as color, zooming, or transparency differences, could be the most effective.

The last implication deals with the transient information effect. Sometimes, long dynamic visualizations whose pace cannot be controlled should be changed to pace control formats, shorter versions, or static visualizations. Similarly, long narrations should be shortened.

5.9.2 Future Research Directions

We note some future directions that research into science visualizations and visuospatial processing might follow. The first direction goes beyond the emphasis of this chapter and of cognitive load theory. When learning through visualizations, there are factors besides cognitive processes to be considered, such as behavioral, motivational, and emotional influences (cf. Fraser et al. 2015). For example, future research could include emotions as variables that influence perceived cognitive load when learning from science visualizations or simulations (e.g., Fraser et al. 2014).

A second direction is based on the point that visualization and multimedia researchers have commonly measured the visuospatial processing abilities of mental rotations with 3D figures and mental folding. However, there are many other visuospatial tasks, such as those measured in tests of 2D mental rotation, field independence, and other visuospatial working memory instruments (see Castro-Alonso and Atit this volume, Chap. 2; see also Castro-Alonso et al. this volume-a, Chap. 8). Future research could investigate the effects of these other visuospatial abilities in learning from science visualizations optimized by cognitive load theory effects. An analogous direction for further research involves studying the effects of visuospatial tests on particular scientific visual and spatial tasks (see Castro-Alonso et al. 2019a).

Third, concerning the modality and signaling principles, there are not many examples of visuospatial processing influencing these principles for science visualizations. Thus, future investigations could study how visuospatial processing interacts with the beneficial effects of the modality and the signaling principles when learning through visualizations depicting health and natural science topics.

A fourth direction, regarding the transient information effect, is that the prediction that visuospatial processing would be more important for animations and videos than for static pictures, was not supported by the research reported here. On the contrary, the studies reviewed in this chapter suggest that visuospatial processing is beneficial for both dynamic and static visualizations. Further investigations about static vs. dynamic visualizations can help reach a stronger prediction whether visuospatial processing is more helpful for static, dynamic, or both formats of visualizations. These efforts would also be benefitted by future investigations tackling moderating variables for static vs. animation research, such as gender (e.g., Castro-Alonso et al. 2019b), the design of the dynamic or static images (see Castro-Alonso et al. 2016), and the strategies learners employ when studying visualizations (see Ayres et al. 2019).

5.9.3 Conclusion

Properly designed instructional static and dynamic visualizations can be useful assets to health and natural science learning. To be effective, the designs should follow guidelines of cognitive load theory and other approaches that investigate the human cognitive architecture for learning. Furthermore, the limitations of visuospatial processing when managing novel visual and spatial information should also be considered in order to design effective visualizations. In this chapter, we described five guidelines, based on well-researched effects, to optimize visualizations, including the influence of visuospatial processing, and providing applications for health and natural sciences education. The guidelines were based on: (a) the split attention effect and spatial contiguity principle, (b) the modality effect, (c) the redundancy effect and coherence principle, (d) the signaling principle, and (e) the transient information effect. Regarding education for health and natural sciences, often these guidelines were most important for low visuospatial processing students.

Acknowledgments This research was partially supported by funds from PIA–CONICYT Basal Funds for Centers of Excellence, Project FB0003, and by a 2018 research grant from the School of Education, University of New South Wales. The first author is thankful to Mariana Poblete for her assistance.

References

Aldahmash, A. H., & Abraham, M. R. (2009). Kinetic versus static visuals for facilitating college students' understanding of organic reaction mechanisms in chemistry. *Journal of Chemical Education, 86*(12), 1442–1446. https://doi.org/10.1021/ed086p1442.

Amadieu, F., Mariné, C., & Laimay, C. (2011). The attention-guiding effect and cognitive load in the comprehension of animations. *Computers in Human Behavior, 27*(1), 36–40. https://doi.org/10.1016/j.chb.2010.05.009.

Ayres, P., & Paas, F. (2007a). Can the cognitive load approach make instructional animations more effective? *Applied Cognitive Psychology, 21*(6), 811–820. https://doi.org/10.1002/acp.1351.

Ayres, P., & Paas, F. (2007b). Making instructional animations more effective: A cognitive load approach. *Applied Cognitive Psychology, 21*(6), 695–700. https://doi.org/10.1002/acp.1343.

Ayres, P., & Sweller, J. (2014). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 206–226). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.011.

Ayres, P., Castro-Alonso, J. C., Wong, M., Marcus, N., & Paas, F. (2019). Factors that impact on the effectiveness of instructional animations. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (pp. 180–193). New York: Routledge. https://doi.org/10.4324/9780429283895-15.

Bauhoff, V., Huff, M., & Schwan, S. (2012). Distance matters: Spatial contiguity effects as trade-off between gaze switches and memory load. *Applied Cognitive Psychology, 26*(6), 863–871. https://doi.org/10.1002/acp.2887.

Berney, S., Bétrancourt, M., Molinari, G., & Hoyek, N. (2015). How spatial abilities and dynamic visualizations interplay when learning functional anatomy with 3D anatomical models. *Anatomical Sciences Education, 8*(5), 452–462. https://doi.org/10.1002/ase.1524.

Biard, N., Cojean, S., & Jamet, E. (2018). Effects of segmentation and pacing on procedural learning by video. *Computers in Human Behavior, 89*, 411–417. https://doi.org/10.1016/j.chb.2017.12.002.

Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences, 105*(38), 14325–14329. https://doi.org/10.1073/pnas.0803390105.

Brünken, R., Steinbacher, S., Plass, J. L., & Leutner, D. (2002). Assessment of cognitive load in multimedia learning using dual-task methodology. *Experimental Psychology, 49*(2), 109–119. https://doi.org/10.1027//1618-3169.49.2.109.

Butcher, K. R. (2014). The multimedia principle. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 174–205). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.010.

Calkins, M. W. (1898). Short studies in memory and in association from the Wellesly College Psychological Laboratory. *Psychological Review, 5*(5), 451–462. https://doi.org/10.1037/h0071176.

Castro-Alonso, J. C., & Atit, K. (this volume). Different abilities controlled by visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 23–51). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_2.

Castro-Alonso, J. C., & Fiorella, L. (this volume). Interactive science multimedia and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 145–173). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_6.

Castro-Alonso, J. C., & Uttal, D. H. (this volume). Science education and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 53–79). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_3.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2014a). Dynamic visualisations and motor skills. In W. Huang (Ed.), *Handbook of human centric visualization* (pp. 551–580). New York: Springer. https://doi.org/10.1007/978-1-4614-7485-2_22.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2014b). Learning from observing hands in static and animated versions of non-manipulative tasks. *Learning and Instruction, 34*, 11–21. https://doi.org/10.1016/j.learninstruc.2014.07.005.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2016). Comparing apples and oranges? A critical look at research on learning from statics versus animations. *Computers & Education, 102*, 234–243. https://doi.org/10.1016/j.compedu.2016.09.004.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018a). Computerized and adaptable tests to measure visuospatial abilities in STEM students. In T. Andre (Ed.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2017 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 337–349). Cham: Springer. https://doi.org/10.1007/978-3-319-60018-5_33.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2018b). Learning symbols from permanent and transient visual presentations: Don't overplay the hand. *Computers & Education, 116*, 1–13. https://doi.org/10.1016/j.compedu.2017.08.011.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2019a). Visuospatial tests and multimedia learning: The importance of employing relevant instruments. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (pp. 89–99). New York: Routledge. https://doi.org/10.4324/9780429283895-8.

Castro-Alonso, J. C., Wong, M., Adesope, O. O., Ayres, P., & Paas, F. (2019b). Gender imbalance in instructional dynamic versus static visualizations: A meta-analysis. *Educational Psychology Review*, *31*(2), 361–387. https://doi.org/10.1007/s10648-019-09469-1.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (this volume-a). VAR: A battery of computer-based instruments to measure visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 207–229). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_8.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (this volume-b). Embodied cognition, science education, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 175–205). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_7.

Chandler, P., & Sweller, J. (1991). Cognitive load theory and the format of instruction. *Cognition and Instruction, 8*(4), 293–332.

Chen, O., Castro-Alonso, J. C., Paas, F., & Sweller, J. (2018). Extending cognitive load theory to incorporate working memory resource depletion: Evidence from the spacing effect. *Educational Psychology Review, 30*(2), 483–501. https://doi.org/10.1007/s10648-017-9426-2.

Cheon, J., Crooks, S., & Chung, S. (2014). Does segmenting principle counteract modality principle in instructional animation? *British Journal of Educational Technology, 45*(1), 56–64. https://doi.org/10.1111/bjet.12021.

Cierniak, G., Scheiter, K., & Gerjets, P. (2009). Explaining the split-attention effect: Is the reduction of extraneous cognitive load accompanied by an increase in germane cognitive load? *Computers in Human Behavior, 25*(2), 315–324. https://doi.org/10.1016/j.chb.2008.12.020.

Clark, J., & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review, 3*(3), 149–210. https://doi.org/10.1007/bf01320076.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale: Erlbaum.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*(1), 87–185. https://doi.org/10.1017/S0140525X01003922.

de Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2009). Towards a framework for attention cueing in instructional animations: Guidelines for research and design. *Educational Psychology Review, 21*(2), 113–140. https://doi.org/10.1007/s10648-009-9098-7.

de Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2010). Learning by generating vs. receiving instructional explanations: Two approaches to enhance attention cueing in animations. *Computers & Education, 55*(2), 681–691. https://doi.org/10.1016/j.compedu.2010.02.027.

Dutke, S., & Rinck, M. (2006). Multimedia learning: Working memory and the learning of word and picture diagrams. *Learning and Instruction, 16*(6), 526–537. https://doi.org/10.1016/j.learninstruc.2006.10.002.

Eitel, A., Scheiter, K., Schüler, A., Nyström, M., & Holmqvist, K. (2013). How a picture facilitates the process of learning from text: Evidence for scaffolding. *Learning and Instruction, 28*, 48–63. https://doi.org/10.1016/j.learninstruc.2013.05.002.

Eitel, A., Bender, L., & Renkl, A. (2019). Are seductive details seductive only when you think they are relevant? An experimental test of the moderating role of perceived relevance. *Applied Cognitive Psychology, 33*(1), 20–30. https://doi.org/10.1002/acp.3479.

Erhel, S., & Jamet, E. (2006). Using pop-up windows to improve multimedia learning. *Journal of Computer Assisted Learning, 22*(2), 137–147. https://doi.org/10.1111/j.1365-2729.2006.00165.x.

Fenesi, B., Kramer, E., & Kim, J. A. (2016). Split-attention and coherence principles in multimedia instruction can rescue performance for learners with lower working memory capacity. *Applied Cognitive Psychology, 30*(5), 691–699. https://doi.org/10.1002/acp.3244.

Fraser, K. L., Huffman, J., Ma, I., Sobczak, M., McIlwrick, J., Wright, B., et al. (2014). The emotional and cognitive impact of unexpected simulated patient death: A randomized controlled trial. *Chest, 145*(5), 958–963. https://doi.org/10.1378/chest.13-0987.

Fraser, K. L., Ayres, P., & Sweller, J. (2015). Cognitive load theory for the design of medical simulations. *Simulation in Healthcare, 10*(5), 295–307. https://doi.org/10.1097/sih.0000000000000097.

Garg, A. X., Norman, G., Spero, L., & Taylor, I. (1999). Learning anatomy: Do new computer models improve spatial understanding? *Medical Teacher, 21*(5), 519–522. https://doi.org/10.1080/01421599979239.

Geary, D. C. (2002). Principles of evolutionary educational psychology. *Learning and Individual Differences, 12*(4), 317–345. https://doi.org/10.1016/s1041-6080(02)00046-8.

Geary, D. C. (2007). Educating the evolved mind: Conceptual foundations for an evolutionary educational psychology. In J. S. Carlson & J. R. Levin (Eds.), *Psychological perspectives on contemporary educational issues* (pp. 1–99). Charlotte: Information Age Publishing.

Geary, D. C., & Berch, D. B. (2016). Evolution and children's cognitive and academic development. In D. C. Geary & D. B. Berch (Eds.), *Evolutionary perspectives on child development and education* (pp. 217–249). Cham: Springer. https://doi.org/10.1007/978-3-319-29986-0_9.

Ginns, P. (2005). Meta-analysis of the modality effect. *Learning and Instruction, 15*(4), 313–331. https://doi.org/10.1016/j.learninstruc.2005.07.001.

Ginns, P. (2006). Integrating information: A meta-analysis of the spatial contiguity and temporal contiguity effects. *Learning and Instruction, 16*(6), 511–525.

Harp, S. F., & Mayer, R. E. (1997). The role of interest in learning from scientific text and illustrations: On the distinction between emotional interest and cognitive interest. *Journal of Educational Psychology, 89*(1), 92–102. https://doi.org/10.1037/0022-0663.89.1.92.

Harp, S. F., & Mayer, R. E. (1998). How seductive details do their damage: A theory of cognitive interest in science learning. *Journal of Educational Psychology, 90*(3), 414–434. https://doi.org/10.1037/0022-0663.90.3.414.

Hasler, B. S., Kersten, B., & Sweller, J. (2007). Learner control, cognitive load and instructional animation. *Applied Cognitive Psychology, 21*(6), 713–729. https://doi.org/10.1002/acp.1345.

Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *Topics in Cognitive Science, 3*(3), 446–474. https://doi.org/10.1111/j.1756-8765.2011.01150.x.

Höffler, T. N., & Schwartz, R. N. (2011). Effects of pacing and cognitive style across dynamic and non-dynamic representations. *Computers & Education, 57*(2), 1716–1726. https://doi.org/10.1016/j.compedu.2011.03.012.

Hosler, J., Boomer, K. B., & Kalumuck, K. (2011). Are comic books an effective way to engage nonmajors in learning and appreciating science? *CBE Life Sciences Education, 10*(3), 309–317. https://doi.org/10.1187/cbe.10-07-0090.

Houts, P. S., Doak, C. C., Doak, L. G., & Loscalzo, M. J. (2006). The role of pictures in improving health communication: A review of research on attention, comprehension, recall, and adherence. *Patient Education and Counseling, 61*(2), 173–190. https://doi.org/10.1016/j.pec.2005.05.004.

Huff, M., & Schwan, S. (2011). Integrating information from two pictorial animations: Complexity and cognitive prerequisites influence performance. *Applied Cognitive Psychology, 25*(6), 878–886. https://doi.org/10.1002/acp.1762.

Huff, M., Bauhoff, V., & Schwan, S. (2012). Effects of split attention revisited: A new display technology for troubleshooting tasks. *Computers in Human Behavior, 28*(4), 1254–1261. https://doi.org/10.1016/j.chb.2012.02.008.

Imhof, B., Scheiter, K., Edelmann, J., & Gerjets, P. (2013). Learning about locomotion patterns: Effective use of multiple pictures and motion-indicating arrows. *Computers & Education, 65*, 45–55. https://doi.org/10.1016/j.compedu.2013.01.017.

Issa, N., Schuller, M., Santacaterina, S., Shapiro, M., Wang, E., Mayer, R. E., et al. (2011). Applying multimedia design principles enhances learning in medical education. *Medical Education, 45*(8), 818–826. https://doi.org/10.1111/j.1365-2923.2011.03988.x.

Jaffar, A. A. (2012). YouTube: An emerging tool in anatomy education. *Anatomical Sciences Education, 5*(3), 158–164. https://doi.org/10.1002/ase.1268.

Kalyuga, S., & Sweller, J. (2014). The redundancy principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 247–262). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.013.

Kalyuga, S., Chandler, P., & Sweller, J. (1999). Managing split-attention and redundancy in multimedia instruction. *Applied Cognitive Psychology, 13*(4), 351–371.

Korbach, A., Brünken, R., & Park, B. (2016). Learner characteristics and information processing in multimedia learning: A moderated mediation of the seductive details effect. *Learning and Individual Differences, 51*, 59–68. https://doi.org/10.1016/j.lindif.2016.08.030.

Kühl, T., Scheiter, K., Gerjets, P., & Edelmann, J. (2011). The influence of text modality on learning with static and dynamic visualizations. *Computers in Human Behavior, 27*(1), 29–35. https://doi.org/10.1016/j.chb.2010.05.008.

Kühl, T., Stebner, F., Navratil, S. C., Fehringer, B. C. O. F., & Münzer, S. (2018). Text information and spatial abilities in learning with different visualizations formats. *Journal of Educational Psychology, 110*(4), 561–577. https://doi.org/10.1037/edu0000226.

Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A. (1980). Expert and novice performance in solving physics problems. *Science, 208*(4450), 1335–1342. https://doi.org/10.1126/science.208.4450.1335.

Lee, D. Y., & Shin, D.-H. (2011). Effects of spatial ability and richness of motion cue on learning in mechanically complex domain. *Computers in Human Behavior, 27*(5), 1665–1674. https://doi.org/10.1016/j.chb.2011.02.005.

Lee, D. Y., & Shin, D.-H. (2012). An empirical evaluation of multi-media based learning of a procedural task. *Computers in Human Behavior, 28*(3), 1072–1081. https://doi.org/10.1016/j.chb.2012.01.014.

Levinson, A. J., Weaver, B., Garside, S., McGinn, H., & Norman, G. R. (2007). Virtual reality and brain anatomy: A randomised trial of e-learning instructional designs. *Medical Education, 41*(5), 495–501. https://doi.org/10.1111/j.1365-2929.2006.02694.x.

Lin, L., & Atkinson, R. K. (2011). Using animations and visual cueing to support learning of scientific concepts and processes. *Computers & Education, 56*(3), 650–658. https://doi.org/10.1016/j.compedu.2010.10.007.

Loftus, J. J., Jacobsen, M., & Wilson, T. D. (2018). The relationship between spatial ability, cerebral blood flow and learning with dynamic images: A transcranial Doppler ultrasonography study. *Medical Teacher, 40*(2), 174–180. https://doi.org/10.1080/0142159X.2017.1395401.

Low, R., & Sweller, J. (2014). The modality principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 227–246). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.012.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279–281. https://doi.org/10.1038/36846.

Mahmud, W., Hyder, O., Butt, J., & Aftab, A. (2011). Dissection videos do not improve anatomy examination scores. *Anatomical Sciences Education, 4*(1), 16–21. https://doi.org/10.1002/ase.194.

Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Role of subjective and objective measures of cognitive processing during learning in explaining the spatial contiguity effect. *Learning and Instruction, 61*, 23–34. https://doi.org/10.1016/j.learninstruc.2018.12.001.

Mayer, R. E. (1989). Systematic thinking fostered by illustrations in scientific text. *Journal of Educational Psychology, 81*(2), 240–246. https://doi.org/10.1037/0022-0663.81.2.240.

Mayer, R. E. (2008). Research-based principles for learning with animation. In R. K. Lowe & W. Schnotz (Eds.), *Learning with animation: Research implications for design* (pp. 30–48). New York: Cambridge University Press.

Mayer, R. E. (Ed.). (2014a). *The Cambridge handbook of multimedia learning* (2nd ed.). New York: Cambridge University Press.

Mayer, R. E. (2014b). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 43–71). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.005.

Mayer, R. E., & Gallini, J. K. (1990). When is an illustration worth ten thousand words? *Journal of Educational Psychology, 82*(4), 715–726. https://doi.org/10.1037/0022-0663.82.4.715.

Mayer, R. E., Griffith, E., Jurkowitz, I. T. N., & Rothman, D. (2008). Increased interestingness of extraneous details in a multimedia science presentation leads to decreased learning. *Journal of Experimental Psychology: Applied, 14*(4), 329–339. https://doi.org/10.1037/a0013835.

Moreno, R., & Mayer, R. E. (1999). Cognitive principles of multimedia learning: The role of modality and contiguity. *Journal of Educational Psychology, 91*(2), 358–368. https://doi.org/10.1037/0022-0663.91.2.358.

Mousavi, S. Y., Low, R., & Sweller, J. (1995). Reducing cognitive load by mixing auditory and visual presentation modes. *Journal of Educational Psychology, 87*(2), 319–334. https://doi.org/10.1037/0022-0663.87.2.319.

Münzer, S., Seufert, T., & Brünken, R. (2009). Learning from multimedia presentations: Facilitation function of animations and spatial abilities. *Learning and Individual Differences, 19*(4), 481–485. https://doi.org/10.1016/j.lindif.2009.05.001.

Nguyen, N., Nelson, A. J., & Wilson, T. D. (2012). Computer visualizations: Factors that influence spatial anatomy comprehension. *Anatomical Sciences Education, 5*(2), 98–108. https://doi.org/10.1002/ase.1258.

Oberauer, K., & Eichenberger, S. (2013). Visual working memory declines when more features must be remembered for each object. *Memory & Cognition, 41*(8), 1212–1227. https://doi.org/10.3758/s13421-013-0333-6.

Ong, W. J. (1982). *Orality and literacy: The technologizing of the word*. New York: Methuen.

Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review, 24*(1), 27–45. https://doi.org/10.1007/s10648-011-9179-2.

Paas, F., & Sweller, J. (2014). Implications of cognitive load theory for multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 27–42). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.004.

Penney, C. G. (1989). Modality effects and the structure of short-term verbal memory. *Memory & Cognition, 17*(4), 398–422. https://doi.org/10.3758/bf03202613.

Purnell, K. N., Solman, R. T., & Sweller, J. (1991). The effects of technical illustrations on cognitive load. *Instructional Science, 20*(5), 443–462. https://doi.org/10.1007/bf00116358.

Rey, G. D. (2012). A review of research and a meta-analysis of the seductive detail effect. *Educational Research Review, 7*(3), 216–237. https://doi.org/10.1016/j.edurev.2012.05.003.

Rey, G. D., Beege, M., Nebel, S., Wirzberger, M., Schmitt, T. H., & Schneider, S. (2019). A meta-analysis of the segmenting effect. *Educational Psychology Review*, *31*(2), 389–419. https://doi.org/10.1007/s10648-018-9456-4.

Richter, J., Scheiter, K., & Eitel, A. (2016). Signaling text-picture relations in multimedia learning: A comprehensive meta-analysis. *Educational Research Review, 17*, 19–36. https://doi.org/10.1016/j.edurev.2015.12.003.

Schmidt-Weigand, F., Kohnert, A., & Glowalla, U. (2010). A closer look at split visual attention in system- and self-paced instruction in multimedia learning. *Learning and Instruction, 20*(2), 100–110. https://doi.org/10.1016/j.learninstruc.2009.02.011.

Schneider, S., Beege, M., Nebel, S., & Rey, G. D. (2018). A meta-analysis of how signaling affects learning with media. *Educational Research Review, 23*, 1–24. https://doi.org/10.1016/j.edurev.2017.11.001.

Schroeder, N. L., & Cenkci, A. T. (2018). Spatial contiguity and spatial split-attention effects in multimedia learning environments: A meta-analysis. *Educational Psychology Review, 30*(3), 679–701. https://doi.org/10.1007/s10648-018-9435-9.

Seufert, T., Schütze, M., & Brünken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude-treatment-interaction study. *Learning and Instruction, 19*(1), 28–42. https://doi.org/10.1016/j.learninstruc.2008.01.002.

Shepard, R. N. (1967). Recognition memory for words, sentences, and pictures. *Journal of Verbal Learning and Verbal Behavior, 6*(1), 156–163. https://doi.org/10.1016/s0022-5371(67)80067-7.

Singh, A.-M., Marcus, N., & Ayres, P. (2012). The transient information effect: Investigating the impact of segmentation on spoken and written text. *Applied Cognitive Psychology, 26*(6), 848–853. https://doi.org/10.1002/acp.2885.

Skulmowski, A., & Rey, G. D. (2018). Realistic details in visualizations require color cues to foster retention. *Computers & Education, 122*, 23–31. https://doi.org/10.1016/j.compedu.2018.03.012.

Spanjers, I. A. E., van Gog, T., & van Merriënboer, J. J. G. (2010). A theoretical analysis of how segmentation of dynamic visualizations optimizes students' learning. *Educational Psychology Review, 22*(4), 411–423. https://doi.org/10.1007/s10648-010-9135-6.

Stiller, K. D., Freitag, A., Zinnbauer, P., & Freitag, C. (2009). How pacing of multimedia instructions can influence modality effects: A case of superiority of visual texts. *Australasian Journal of Educational Technology, 25*(2), 184–203. https://doi.org/10.14742/ajet.1149.

Stull, A. T., Gainer, M. J., & Hegarty, M. (2018). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction, 55*, 80–92. https://doi.org/10.1016/j.learninstruc.2017.09.008.

Sweller, J. (2015). In academe, what is learned, and how is it learned? *Current Directions in Psychological Science, 24*(3), 190–194. https://doi.org/10.1177/0963721415569570.

Sweller, J. (2016). Cognitive load theory, evolutionary educational psychology, and instructional design. In D. C. Geary & D. B. Berch (Eds.), *Evolutionary perspectives on child development and education* (pp. 291–306). Cham: Springer. https://doi.org/10.1007/978-3-319-29986-0_12.

Sweller, J., & Sweller, S. (2006). Natural information processing systems. *Evolutionary Psychology, 4*, 434–458.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York: Springer.

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive architecture and instructional design: 20 years later. *Educational Psychology Review*, *31*(2), 261–292. https://doi.org/10.1007/s10648-019-09465-5.

Tarmizi, R. A., & Sweller, J. (1988). Guidance during mathematical problem solving. *Journal of Educational Psychology, 80*(4), 424–436. https://doi.org/10.1037/0022-0663.80.4.424.

Tricot, A., & Sweller, J. (2014). Domain-specific knowledge and why teaching generic skills does not work. *Educational Psychology Review, 26*(2), 265–283. https://doi.org/10.1007/s10648-013-9243-1.

van Gog, T. (2014). The signaling (or cueing) principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 263–278). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.014.

Vekiri, I. (2002). What is the value of graphical displays in learning? *Educational Psychology Review, 14*(3), 261–312. https://doi.org/10.1023/a:1016064429161.

Wiegmann, D. A., Dansereau, D. F., McCagg, E. C., Rewey, K. L., & Pitre, U. (1992). Effects of knowledge map characteristics on information processing. *Contemporary Educational Psychology, 17*(2), 136–155. https://doi.org/10.1016/0361-476X(92)90055-4.

Wilson, T. D. (2015). Role of image and cognitive load in anatomical multimedia. In L. K. Chan & W. Pawlina (Eds.), *Teaching anatomy: A practical guide* (pp. 237–246). Cham: Springer. https://doi.org/10.1007/978-3-319-08930-0_27.

Wong, A., Leahy, W., Marcus, N., & Sweller, J. (2012). Cognitive load theory, the transient information effect and e-learning. *Learning and Instruction, 22*(6), 449–457. https://doi.org/10.1016/j.learninstruc.2012.05.004.

Xie, H., Wang, F., Hao, Y., Chen, J., An, J., Wang, Y., et al. (2017). The more total cognitive load is reduced by cues, the better retention and transfer of multimedia learning: A meta-analysis and two meta-regression analyses. *PLoS One, 12*(8), e0183884. https://doi.org/10.1371/journal.pone.0183884.

Youssef, A., Ayres, P., & Sweller, J. (2012). Using general problem-solving strategies to generate ideas in order to solve geography problems. *Applied Cognitive Psychology, 26*(6), 872–877. https://doi.org/10.1002/acp.2888.

Chapter 6
Interactive Science Multimedia and Visuospatial Processing

Juan C. Castro-Alonso and Logan Fiorella

An educational setting of interactive science multimedia involves at least two agents: the student and the multimedia. Both agents *interact* by giving and receiving information. Multimedia instructional designers aim to enhance these exchanges of information (see Domagk et al. 2010) when producing the myriad of interactive educational products available. Moreno and Mayer (2007) proposed a classification of this diverse offer of multimedia products, based on three levels of increasing interactivity:

- Level 1: Low interactive tools entail students *dialoguing* with the multimedia. For example, learners can solve a problem presented on-screen. This level of dialoguing is generally included in computer-based instruction, digital libraries, and similar multimedia presentations.
- Level 2: Medium interactive tools allow learners *controlling* the multimedia. For example, students can pause and rewind a presentation. This level is generally included in animations and videos.
- Level 3: High interactive tools allow students *manipulating* the multimedia. For example, learners can drag objects around the screen. Manipulating is generally included in simulations and videogames.

In short, simulations and videogames allow the greatest interactive capabilities between the students and the multimedia. As the bottom levels contain the top ones, simulations and videogames allow students all three degrees of action: dialoguing, controlling, and manipulating. Given this high potential for interactivity, simulations and videogames are the focus of the current chapter.

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

L. Fiorella
Department of Educational Psychology, University of Georgia, Athens, GA, USA

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_6

Although there are two agents involved in an interaction event, educational research on interactive science multimedia must focus on the first agent, the student. As warned by Mayer (2014), multimedia learning research should primarily investigate the students' mental processes, rather than the multimedia's capabilities. This approach can help ensure that multimedia design supports mental processes necessary for meaningful learning.

However, there are many mental processes in which students engage during interactive science multimedia learning. As described in the *integrated model of multimedia interactivity* (INTERACT; see Domagk et al. 2010), the students are involved in motivational, behavioral, and cognitive processes. In this chapter, we will focus on cognitive processes and specifically the role of students' visuospatial processing. We begin by describing different research perspectives that can help foster effective student–multimedia interactions.

6.1 Research Perspectives on Fostering Effective Interactivity

In all interactive multimedia learning situations, including those about health and natural science topics in university education, the student and multimedia are agents that exchange information. In a dialogue of giving and receiving information, the student engages in an action, which is responded by the multimedia as feedback, so the learner can generate a more appropriate action, receive feedback again, and so forth (see Domagk et al. 2010). Different research areas have investigated analogous dialogues in educational settings. We will describe them here as *engagement* by the student and *feedback* by the multimedia (see Fig. 6.1). As we note next, findings from research on engagement and feedback have provided guidelines to foster more effective learning with interactive science multimedia.

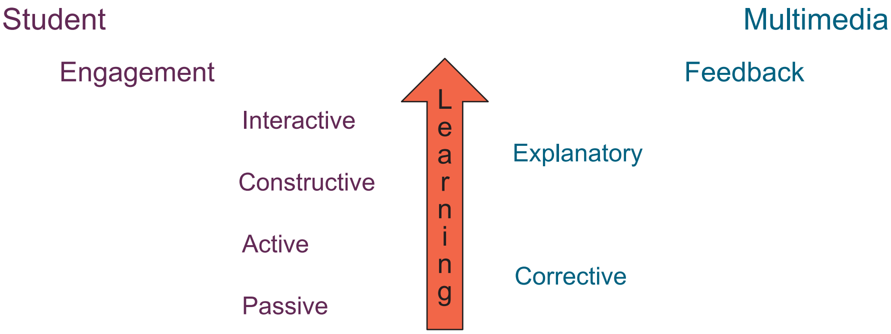


Fig. 6.1 Agents, actions, and degrees in an interactive multimedia learning event

6.1.1 Student Engagement

Chi and Wylie (2014) described the *ICAP framework* of cognitive engagement. This framework can be linked to other educational approaches, such as *generative learning* (see Fiorella and Mayer 2015, 2016) or *embodied cognition* (see Castro-Alonso et al. this volume-c, Chap. 7; see also Castro-Alonso et al. 2015). These research perspectives share that higher *cognitive* engagement can boost learning. As framed by the ICAP model (Chi and Wylie 2014) and discussed by Mayer (2014), it is important to distinguish between cognitive and behavioral engagement (e.g., hands-on activities). Although these types of engagement can be related, cognitive engagement is the primary driver of understanding, whereas behavioral engagement *per se* does not necessarily enhance learning. Thus, in general, higher cognitive engagement, independent of behavioral activities, will lead to higher quality learning outcomes.

The ICAP framework distinguishes among four degrees of cognitive engagement (see Fig. 6.1): *interactive*, *constructive*, *active*, and *passive* (ICAP). The framework predicts that learning activities fostering constructive and interactive cognitive engagement will be more successful than activities that only foster passive and active engagement. For example, the framework promotes science multimedia that allow both constructive engagement, in which students develop new ideas, and interactive engagement, in which students test those ideas and receive feedback from the multimedia. Note that these two top levels of engagement in the ICAP framework correspond to the highest level (Level 3, see above) of the model by Moreno and Mayer (2007). As such, constructive and interactive cognitive engagement is characteristic of learning through simulations and videogames.

For interactive multimedia, the evidence with university students shows that creating higher levels of engagement can produce better learning outcomes (e.g., Wiley 2019). Much of this research supports active over passive engagement. For example, Erhel and Jamet (2006) investigated 72 psychology undergraduates (85% females) learning health science topics from multimedia modules presented in different formats. Results showed that the most effective design was the one allowing students to click parts of the images to reveal corresponding blocks of texts (active), as compared to conditions in which clicking was not allowed (passive). In a study by Evans and Gibbons (2007), 33 business undergraduates (33% females) studied multimedia depicting the mechanisms of a bicycle pump. Students were randomly assigned to learn from a lesson without interactive features or to learn from a lesson that allowed the engagement activities of: (a) controlling the pace of the presentation, (b) testing questions, and (c) triggering a simulation of the pump. Results indicated that the interactive group outperformed the non-interactive group on a subsequent transfer test.

Schwartz and Plass (2014) compared passive, active, and constructive levels of engagement. They presented 112 university students with a multimedia lesson that narrated action phrases (e.g., “paint the fence”). Students were randomly assigned to one of three engagement conditions: (a) *look* (passive), in which images for the action (e.g., paintbrush and fence) were shown as static images; (b) *click* (active), in which participants pointed and clicked the images, and these actions resulted in the images becoming animated for the action; and (c) *drag* (constructive), in which participants dragged the images in order to generate the action by themselves. Recall and recognition tests for the action phrases showed that the best performance was for the *drag* condition, followed by *click*, and then *look*. In other words, consistent with the ICAP framework, the possibility of generating dragging movements on the screen (constructive) was better for memory tests than watching the movements already performed after clicking (active), which was also better than solely looking at the screen (passive).

Nevertheless, not all engagement activities are equally effective for multimedia learning. For example, Karich et al. (2014) conducted a meta-analysis of learner control in educational technology research, based on 18 studies ($k = 25$ comparisons and a total $N = 3{,}618$ participants). The analysis investigated the influence of providing learner control over various features of multimedia lessons, including the pacing of the visualizations, ordering of the modules, and opportunities for practice. Overall, the effect of providing these engagement options was of $g = 0.05$, which corresponds to a small effect size according to the benchmarks by Cohen (1988). This small effect suggests that allowing students to control aspects of the learning material may not be the most robust method of fostering productive engagement with multimedia.

Particularly problematic are the engagement actions that induce high cognitive load and thus leave fewer working memory resources available to learning (see Castro-Alonso et al. this volume-b, Chap. 5; see also Mayer and Fiorella 2014). For example, in an experiment with 144 medicine undergraduates studying stroke symptoms from interactive multimedia, Song et al. (2014) randomly assigned students to four different levels of engagement. Two of the groups involved high cognitive engagement, as they required careful consideration of the answer before either clicking or dragging with the mouse. This careful consideration involved using the mouse to find the location of the blockage causing the stroke. These high cognitive action groups performed significantly lower on a subsequent transfer test than the groups involving less cognitive interactivity, which did not require finding the strokes position (see also Kalet et al. 2012).

Similarly, in three experiments totaling 370 university students (66% females), Stull and Mayer (2007) investigated the instructional effectiveness of using concept maps as aids to learning the reproductive barriers between species. The three studies, which differed in the complexity of the concept maps, randomly assigned students to a *learner-generated* condition (concepts maps were built by the students) or a *multimedia-provided* group (concept maps were shown to students). Results across the three experiments consistently showed that the multimedia-provided group outperformed the learner-generated group on transfer tests. As predicted by cognitive load theory, and in contrast to the ICAP framework, generating concept maps required excessive activity, which may have taxed working memory and hindered learning.

In a study by Fiorella and Mayer (2012) college students played an educational game teaching them about how electric circuits work. In the first experiment, students who were provided with a worksheet listing the underlying physics principles taught in the game outperformed students not provided with a worksheet on a subsequent transfer test. However, in the second experiment, participants had to use the worksheet to generate the physics principles on their own while playing the game. Results indicated that only a small group of students who were able to generate the principles accurately benefited from filling in the worksheet, whereas most students could not generate the principles on their own. These findings highlight the potential limitations of engaging students by asking them to generate content on their own.

In all, research on cognitive engagement—and related findings of generative learning and embodied cognition—predict that multimedia lessons that allow higher cognitive engagement, such as by incorporating interactive and constructive activities, will be more effective than lessons allowing less engagement, such as active and passive activities. However, when the multimedia is already highly complex and taxes the necessary working memory to deal with the learning elements, adding excessive engagement activities could be counterproductive (see also Fiorella et al. 2012a).

Thus, a balanced degree of engagement should be provided to the student, particularly to those with a lower capacity of working memory or visuospatial processing. As described next, in addition to these engagement possibilities of the learner, how the multimedia responds to learner engagement plays an essential role in supporting meaningful learning.

6.1.2 Multimedia Feedback

In the broader educational research literature, Hattie and Timperley (2007) defined feedback as information provided by an agent related to the learner's understanding or performance. In interactive multimedia learning events, the agent is the multimedia, which provides feedback in response to students' engagement activities. Feedback has also been termed as *scaffolding* or *guidance* in the literature on learning from simulations (e.g., Fraser et al. 2015).

There are two broad levels of feedback: *feedback about the task* and *feedback about the processing of the task* (Hattie and Timperley 2007). In a review of simulations and educational videogames, Johnson et al. (2017) termed these levels *outcome feedback* and *process feedback,* respectively. In the multimedia learning literature (e.g., Moreno 2004; Moreno and Mayer 2007), these levels are commonly called *corrective feedback* and *explanatory feedback* (see Fig. 6.1). An example of corrective (lower-level) feedback is hearing a cheerful sound after providing a correct answer in a simulation or videogame (cf. Miranda and Palmer 2014). This level of feedback is the most common but may only lead to surface learning or non-improved performance (e.g., Adam and Vogel 2018).

In contrast, explanatory (higher-level) feedback can lead to deep learning and better performance. For example, a chemistry simulation could show two representations of the same molecule so that when learners manipulate one representation, they see the effects on the other format and can understand their relationship (cf. Barrett et al. 2015). In multimedia research, fostering a more complete and deeper explanatory feedback over the shallower corrective option is referred to as the *guided feedback hypothesis* (Moreno 2004) or the *feedback principle* (Moreno and Mayer 2007).

Research on learning from science multimedia among university students supports the feedback principle. For example, Van der Kleij et al. (2015) conducted a meta-analysis of 40 studies (k = 70 effect sizes) to investigate the effectiveness of three levels of feedback in computer learning environments. Many of the studies concerned science subjects (41%) and university or college students (80%). The levels of feedback consisted of: (a) *knowledge of results*, which solely signaled if the answer was correct or incorrect; (b) *knowledge of correct response*, which signaled if the answer was correct or incorrect, and also revealed the correct answer; and (c) *elaborated feedback*, which signaled if the answer was correct or incorrect, revealed the correct answer, and also elaborated on the given information. Overall, the meta-analysis showed that elaborated feedback was more effective than the lower levels, yielding a medium effect size (g = 0.49). More recently, a review by Rivière et al. (2018) similarly highlighted the importance of deep feedback for medical simulations, and Johnson et al. (2017) also recommended providing detailed feedback when designing military and science simulations.

The videogame literature also supports providing more in-depth feedback. For example, Moreno (2004) reported two experiments with a total of 104 psychology undergraduates that learned from a videogame involving the design of plants for different weather conditions. In each experiment, students were randomly assigned to either the explanatory feedback condition (a narration explained the correctness or incorrectness of each answer) or the corrective feedback group (a narration only communicated whether each answer was right or wrong). Both experiments showed that the explanatory feedback groups had higher transfer test scores and gave higher ratings of feedback helpfulness than the corrective feedback conditions.

A follow-up study by Moreno and Mayer (2005, Experiment 1) with a similar botany multimedia videogame also compared explanatory and corrective feedback. In the experiment with 105 psychology undergraduates (70% females), students in the explanatory feedback conditions achieved higher transfer scores and gave better explanations for their choices, compared to participants receiving only corrective feedback. Recently, meta-analyses of videogames for education by Clark et al. (2016) found that including elaborated feedback in the videogames led to greater learning than providing simpler feedback (indicating errors or displaying the correct answers).

Why is explanatory feedback useful? Johnson and Priest (2014; see also Johnson et al. 2017) argue that the primary purpose of feedback is to help students learn from mistakes. As such, explanatory feedback provides complete information that guides students on how to improve their current level of understanding or performance. In contrast, corrective feedback only informs whether students answered correctly or incorrectly, so it does not provide students with a clear direction for improvement. Without this information, students may try to figure out the correct answer themselves, likely taxing working memory resources and hindering performance. This explanation is consistent with cognitive load theory (see Castro-Alonso et al. this volume-b, Chap. 5; see also Sweller et al. 2011), which predicts that explanatory feedback will be more effective because it provides students with necessary support, whereas corrective feedback creates extraneous cognitive load that hinders learning.

In addition to providing insufficient information, feedback that contains unnecessary or irrelevant information can create extraneous cognitive load and be counterproductive for learning (see the coherence principle in Mayer and Fiorella 2014). Consequently, the most effective explanatory feedback is that including only essential information. As with engagement, extra feedback can sometimes be detrimental for learning, especially if: (a) the multimedia is complex, so it already places heavy demands on students' limited working memory capacity; and (b) the student has a lower capacity of working memory or visuospatial processing, so these systems get overloaded more easily (see also Sect. 6.2.2).

An example of this problematic feedback is provided by L. Lin and Li (2018), who investigated 116 university students (74% females) learning from physics simulations about how objects are affected by phenomena such as friction and gravity. The students were randomly assigned to three feedback groups: (a) *control*, which was not given any visual feedback; (b) *irrelevant feedback*, which was shown their individual brain waves of attention after watching each simulation; and (c) *irrelevant plus relevant feedback*, which was shown the same brain waves plus being prompted to reflect on their learning verbally. The results showed no effects on learning performance or time. However, the ratings of perceived attentiveness and perceived value were significantly lower for both feedback conditions, compared to the control group. Because these formats of feedback were creating additional cognitive load, this processing possibly diverted the students' working memory resources away from the core learning activities.

Finally, a study by Fiorella et al. (2012b) indicates that the modality of explanatory feedback can also influence cognitive load and significantly impact performance during complex learning. In the experiment, 60 undergraduates (40% females) completed military call-for-fire tasks within a simulated environment and received either visual feedback, auditory feedback, or no feedback. Results indicated that receiving auditory feedback led to the highest performance on a subsequent transfer task. Apparently, the visual feedback competed for cognitive resources with the other complex visual information in the simulated environment. In contrast, auditory feedback allowed students to process the simulated environment and the feedback simultaneously (see also the modality effect in Low and Sweller 2014; see Castro-Alonso et al. this volume-b, Chap. 5).

In all, student engagement and multimedia feedback are the exchanges of information that allow learning from interactive multimedia. Findings across several studies involving university students of health and natural science topics indicate that deeper engagement and feedback tend to promote meaningful learning outcomes. Nonetheless, it is also important to avoid overloading working memory with too much cognitive engagement or unnecessary and irrelevant visual feedback, which could be especially counterproductive for students with low visuospatial processing capacity. These conclusions should be considered when designing any interactive multimedia, including the science simulations described next.

6.2 Simulations

According to Johnson et al. (2017), simulations are models of a real-world system in which the user tests variables to learn how they affect the system. Simulations can provide several advantages for science learning when compared to real laboratory activities, which also test variables in a system.

Concerning these advantages, Triona and Klahr (2003) observed that simulations are preferable to physical laboratories for: (a) lower costs of replication and distribution of the activities, (b) more manageable data collection and thus faster data analysis, and (c) reduction or amplification of spatial and temporal dimensions. Brinson (2015) adds the advantages of: (a) visualizing otherwise unobservable phenomena; and (b) removing confusing physical laboratory details, such as equipment miscalibrations or errors. Also, the time savings of using simulations can be substantial, considering that less dexterity is needed to manipulate and assemble virtual materials compared to real components (Klahr et al. 2007).

Furthermore, Potkonjak et al. (2016) noted that simulations are important for: (a) saving money, as they elude buying reactants and real equipment; and (b) flexibility, as many elements of the simulations can be changed (e.g., parameters, apparatus) to produce novel experiences that would be much more difficult in real settings. Another advantage of simulations, which is also present in videogames, is what Plass et al. (2015) called *graceful failure*. The feature, also discussed in Triona and Klahr (2003; see also Potkonjak et al. 2016), takes advantage of the unique opportunity simulations give students to fail without consequences. Failing and trying again has less significant consequences with simulations than in real-world settings, encouraging students to take risks, try novel approaches, and learn from mistakes.

Nevertheless, Potkonjak et al. (2016) observed that the graceful failure advantage could also be a drawback. This disadvantage is that students may respond to the lack of real-world consequences by engaging with the simulation carelessly. Another disadvantage of simulations versus physical laboratories, noted by Brinson (2015), is that simulations may not train for science activities in the real world, but only in ideal scenarios. A summary of these advantages and potential disadvantages of simulations is shown in Table 6.1.

Table 6.1 Advantages and (potential) disadvantages of simulations versus physical laboratories

Outcome	Example
Advantage	Lower costs of replication and distribution
	More manageable data collection and faster data analysis
	Reduction or amplification of spatial and temporal dimensions
	Visualizing unobservable phenomena
	Removing confusing physical laboratory details
	Less dexterity needed for manipulating the virtual materials
	No need to buy real reactants and equipment
	Many elements can be changed to produce novel experiences
	Allow learning from mistakes
Disadvantage	Careless engagement with the simulation
	Not science of the real world

6.2.1 Simulations and Science Education

Several reviews (e.g., Brinson 2015; Plass and Schwartz 2014; Potkonjak et al. 2016; Smetana and Bell 2011) have discussed the beneficial instructional effects of simulations and virtual laboratories on different health and natural science disciplines. For example, the review by Smetana and Bell (2011), which included 61 articles of natural science education from the elementary to the university levels, showed that these interactive multimedia tools promoted: (a) science *content knowledge*; (b) *conceptual change*; and (c) science *process skills*, such as visualization, classification, and experimental design. Similarly, Brinson (2015) included six learning outcomes of simulations (and physical laboratories) in his *KIPPAS* nomenclature: *Knowledge & Understanding*, *Inquiry Skills*, *Practical Skills*, *Perception*, *Analytical Skills*, and *Social & Scientific Communication*. For example, Fig. 6.2 shows a medicine simulation fostering practical skills.

The benefits of simulation-based learning have been documented in studies across a wide range of science areas, including: (a) anatomy (Nicholson et al. 2006), (b) neuroanatomy (Allen et al. 2016), (c) surgery (Keehner et al. 2006; Kostusiak et al. 2017), (d) emergency medicine (Ilgen et al. 2013), (e) nurse skills (Donovan et al. 2018), (f) cell biology (Parong and Mayer 2018), (g) biotechnology (Bonde et al. 2014), (h) chemistry (Blackburn et al. 2019), and (i) geology (Piburn et al. 2005).

For example, the study by Nicholson et al. (2006) illustrates the importance of student engagement in an anatomy simulation. The authors investigated 57 medicine undergraduates learning ear anatomy from either a three-dimensional (3D) interactive simulation or two-dimensional (2D) non-interactive images. The 3D interactive version allowed students to manipulate an ear model across its three axes, as well as to pan and zoom their view of the model. Results showed that the interactive multimedia was a more effective learning tool, arguably because it

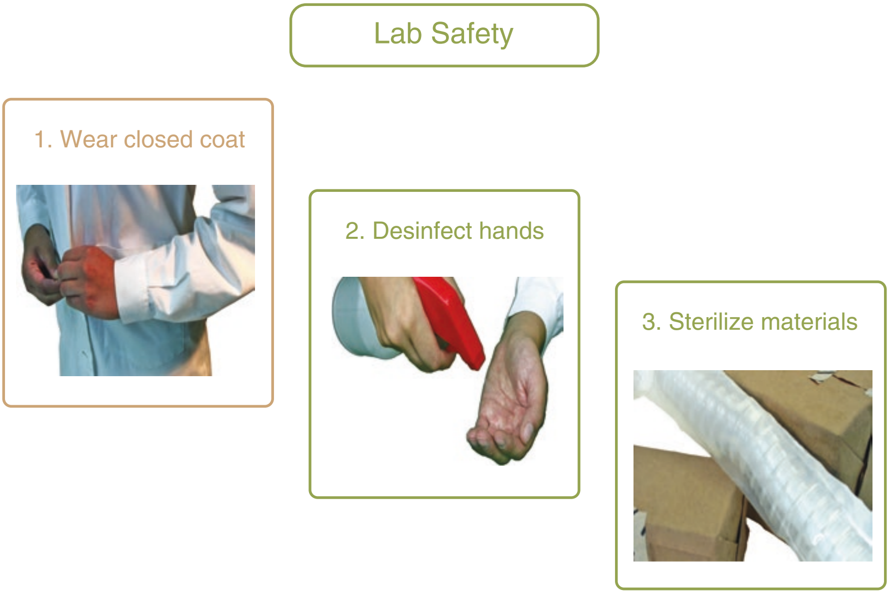


Fig. 6.2 A medicine simulation fostering the practical skills of laboratory safety

allowed more productive cognitive engagement by the student. Similarly, Piburn et al. (2005), in a study with 103 geology university students (53% females), reported positive effects of an interactive multimedia lesson on a geospatial test that included items with topographic maps and cross-sections (see Sect. 6.2.2).

In conclusion, simulations are useful tools for learning health and natural science topics. In a review of simulations for secondary science education, Rutten et al. (2012) discussed that moving the field forward should involve adopting a *zoomed out perspective* that considers the broader educational context. In other words, the design of educational science simulations must consider the role of additional cognitive, motivational, and social factors likely to influence learning. As we describe next, one factor that can moderate learning from simulations is the students' visuospatial processing ability.

6.2.2 Simulations and Visuospatial Processing

Further information about visuospatial processing abilities and instruments is in Castro-Alonso and Atit (this volume, Chap. 2), and similar instruments are described in Castro-Alonso et al. (this volume-a, Chap. 8) and in Castro-Alonso et al. (2018). In this section, we focus on how visuospatial ability helps to learn from simulations in health and natural sciences.

Several studies within the health sciences, particularly in the context of learning anatomy, have established a link between visuospatial ability and simulation-based learning. For example, in a study by Garg et al. (2001), 146 university anatomy students (50% females) learned from a human hand bones model. They found that 3D mental rotation, a spatial ability measured with the Mental Rotations Test, was a significant predictor of success in the visual anatomy test.

Similarly, in a study with 29 adults (35% females), Loftus et al. (2017) observed that high scorers on the Mental Rotation Test outperformed lower scorers in solving human thorax and ankle anatomy tests with static images. Finally, Allen et al. (2016) investigated 47 medicine undergraduates learning neuroanatomy from both an interactive 3D brain simulation and cadaveric brains. Results indicated that performance on neuroanatomy tests was correlated with scores on a computer spatial ability test that involved imagining 2D sections from complex 3D shapes.

Keehner et al. (2006) examined the role of visuospatial processing in learning from surgery simulations. Forty-four university students completed two pen-and-paper instruments of mental rotation (including the Mental Rotations Test). The authors aggregated the results of both tests into a global score. Then, participants trained for 12 sessions within a virtual reality simulation of an angled laparoscopic surgical task. Results indicated that the simulation enhanced students' surgical skills, and further, that mental rotation score was correlated to performance (even in the last session). Thus, this study highlights the important role of mental rotation ability in learning from laparoscopic simulations.

Within the natural sciences, biology visualizations and simulations generally demand students' visuospatial processing (see Castro-Alonso and Uttal 2019). For example, Huk (2006) investigated 106 high school and undergraduate biology students (67% females) learning the structure and function of plant and animal cells from visualizations. Half of the participants also used interactive 3D models of the cells. The Tube Figures Test, a 3D mental rotation test, was used to measure students' visuospatial processing ability. The results showed that only high spatial students could cope with the mental demands imposed by 3D models, and thus profit from interacting with these sophisticated tools.

Similarly, in an experiment with 112 high school biology students (64% females), Huk and Steinke (2007) assessed participants' learning about the structures of plant and animal cells from interactive visualizations. Two instructional techniques for presenting the visualizations were compared: (a) *close-up*, zooming the visualizations; and (b) *connecting lines*, showing links between the cell structures and verbal labels. Using a median split of the Tube Figures Test scores, students were categorized as high- and low-spatial ability individuals. Results indicated that students with high spatial ability outperformed the low spatial students, especially for the condition with the connecting lines. Overall, these studies suggest that visuospatial ability is important for learning from interactive biology multimedia that demand students' engagement.

Visuospatial processing also aids learning from simulations and interactive visualizations about other natural science topics. For example, Urhahne et al. (2009) reported two studies totaling 92 chemistry and biochemistry undergraduates (54%

females) learning about modifications of carbon from interactive 3D simulations or non-interactive 2D illustrations. Regression analyses revealed that spatial ability was a significant predictor of performance for conceptual knowledge tests, but not factual knowledge tests.

Concerning geology, Piburn et al. (2005) reported a quasi-experiment with 103 university students (53% females) in which the experimental group was given a multimedia with interactive 3D blocks to visualize complex geologic structures. The experimental group was compared to a passive control group that did not interact with the 3D blocks. All participants completed measures of 3D mental rotation (adapted Mental Rotations Test) and mental folding (adapted Surface Development Test). As expected, the treatment with interactive multimedia increased the scores in a geospatial test that included tasks with topographic maps, geologic cross-sections, and perspective taking. Moreover, mental folding (but not 3D mental rotation) was a significant predictor of performance on the geospatial test.

Finally, in three experiments totaling 180 undergraduates, Keehner et al. (2008) investigated the influence of 3D mental rotation on tasks that involved cross-sections of a complex 3D shape with internal branches in different directions. The experiments showed that high mental rotators outperformed lower mental rotators on tasks with the complex shape. These effects were observed in both the interactive version (which allowed rotating and moving the complex shape) and the non-interactive format (which did not allow these generative activities). Also, attempting the tasks was equally effective after studying the interactive or non-interactive versions. In conclusion, these findings provided additional support for mental rotation as an effective multimedia learning aid, and also showed that not all generative or engagement activities help when studying multimedia or simulations.

6.3 Videogames

Videogames have also been termed *computer games*, *digital games*, *online games*, and *web-based games* (see Cheng et al. 2015). In recent years, research has accumulated showing the effectiveness of these products for enhancing learning (e.g., Wouters and van Oostendorp 2017; see also Tobias et al. 2014). For example, in two meta-analyses comprising 69 studies and more than 6,600 school and university students, Clark et al. (2016) investigated the learning effects of training with videogames on several disciplines, including psychology, maths, literacy, and science (among others). The first meta-analysis (13% science studies) contrasted the learning effects of training with videogames vs. other forms of training. This analysis showed an overall small to medium effect ($g = 0.33$) favoring videogames.

The second meta-analysis (17% of science studies) compared the learning effects of playing a non-enhanced vs. playing an enhanced educational videogame. The enhancement was provided by guidelines known to benefit learning from videogames, such as feedback, collaboration, and competition. This value-added meta-analysis also showed an overall small to medium effect ($g = 0.34$) favoring enhanced over non-enhanced educational videogames. These meta-analyses indicate not only that videogames can generally be effective assets for learning various disciplines including science, but also that their design based on established instructional principles can further enhance learning.

Research has provided two positive and two potentially negative outcomes of playing videogames for science education. On the positive side, playing properly designed educational videogames can enhance the learning of topics within the health and natural sciences. Also beneficial is the finding that videogaming can help train visuospatial processing abilities, because these abilities are positively related to science learning (see Castro-Alonso and Uttal this volume, Chap. 3).

On the negative side, playing videogames can sometimes result in wasting time instead of investing it in educational activities. This negative outcome is usually reported for entertainment videogames, not for educational videogames. Another potential negative result connects videogame play, particularly the genre of action entertainment videogames, to aggressive behavior. A summary of these four educational outcomes is shown in Table 6.2.

Researchers investigating the first adverse outcome argue that devoting time to entertainment-based videogames can reduce time devoted to learning (e.g., Weis and Cerankosky 2010; see also Cummings and Vandewater 2007). Of course, this logic can be applied to any activity that is not directly relevant to learning. In addition, research suggests that not all videogame time competes with learning. For example, in a study involving a large sample of high school students ($N > 30{,}000$, ~51% females, 14–18 years), Hartanto et al. (2018) investigated the correlations between self-reported videogame play and scores on standardized academic tests (including natural science). Results showed small *negative* correlations in *weekday* videogaming, but smaller and *positive* correlations in *weekend* videogaming. This suggests that there might only be negative effects when videogaming interferes with academic duties (in weekdays), but potentially positive or negligible effects when gameplay takes place primarily on the weekend, at a time when gaming interferes less with educational responsibilities.

The second potential negative viewpoint predicts that playing videogames can lead to aggressive behavior in students (e.g., J.-H. Lin 2013), which should negatively affect learning. However, Ferguson (2010) discussed several empirical and theoretical problems with this perspective. One main problem is that aggressive behavior among the general population has generally decreased, whereas action videogame consumption has rapidly accelerated. Ferguson (2007) provides additional evidence in two meta-analyses relating action videogames to either aggressive

Table 6.2 Types of educational outcomes for videogame playing

Type of outcome	Example
Positive	Science learning
	Visuospatial processing
Negative	Wasted time
	Aggressive behavior

behavior or positive outcomes such as visuospatial cognition. The aggressive behavior meta-analysis ($k = 21$ effect sizes; $N = 3{,}602$ participants) showed less than 1% of the shared variance between action videogame playing and aggression. Thus, the hypothesis that action videogaming can lead to aggression was not supported (see also a recent controlled experiment in Hilgard et al. 2019). In contrast, the positive outcome meta-analysis ($k = 14$, $N = 384$) showed a 13% overlap of variance between action videogame playing and visuospatial processing. This positive relationship is addressed in later sections (see Sects. 6.3.2, 6.3.3 and 6.3.4). The other positive relationship, which links videogaming to science learning, is discussed next.

6.3.1 Videogames and Science Education

The diversity of research on videogames for science education is growing (Fig. 6.3 shows an example of a biology videogame). As such, a comprehensive review by Boyle et al. (2016) showed that the most popular learning areas for research on educational videogames were health sciences (32% of the studies), followed by natural sciences (17%) and computing (10%). The review also showed that most of the designs for these investigations were quasi-experiments (46%), surpassing true experiments (15%) and correlational designs (10%). In a literature review of

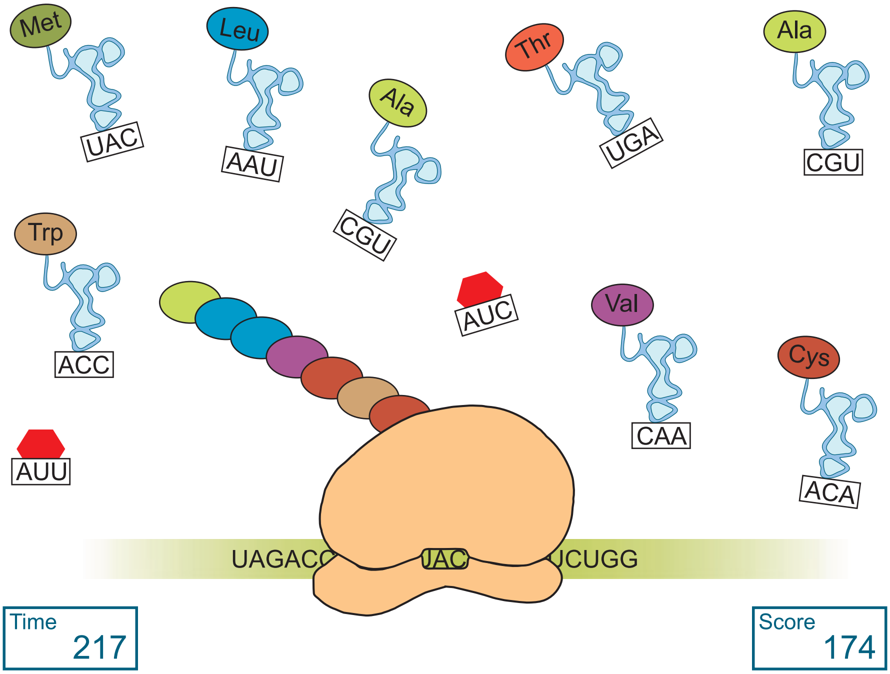


Fig. 6.3 A biology videogame about DNA translation

videogames for natural science education, Cheng et al. (2015) reported that most of the studies focused on interdisciplinary sciences (47%), followed by biology (31%) and physics (22%). This review also showed fewer examples of university-level education in natural sciences, as only 16% of studies covered this level, compared to 72% dealing with school-level samples. Regarding the seven genres of games reviewed, adventure or role-playing (55%) and simulation (21%) were the two most common for natural science education. This is not surprising, as these types of games include avatars and situations where solving problems and engaging in inquiry activities can lead to meaningful learning. In short, there is ample interest in investigating the effects of videogames on science education across diverse research designs, academic disciplines, and games genres.

However, more important than the diversity of research is whether there is empirical evidence showing that videogames are effective tools for learning health and natural science topics. The meta-analysis by Clark et al. (2016), described above, showed positive relationships between videogaming and learning different disciplines, including many science topics. Also, the review by Mayer (2019) showed that in 12 out of 16 experiments, science videogames produced higher learning scores than other science media (e.g., slideshow presentations and web tutorials).

In addition, a number of studies also show positive effects of videogames for university and school students within the disciplines of surgery (Lynch et al. 2010), immunology (Cheng et al. 2014), botany (Moreno 2004; Moreno and Mayer 2005), and physics (Anderson and Barnett 2011). A related variable to science education is the relationship between playing videogames and visuospatial processing.

6.3.2 Videogames and Visuospatial Processing

Arguably, more studies have investigated the relationship between videogames and visuospatial processing than between these games and science education. For example, the systematic review by Cheng et al. (2015) highlighted this focus of research on videogames. The report showed that fewer studies investigated science learning outcomes (14%) compared to cognitive skills (55%), and most studies involving cognitive skills focused on visuospatial processing ability.

There are two types of research investigating the relationships between videogames and visuospatial processing: *correlational* and *experimental* (see Table 6.3). The correlational evidence emerges from comparing the visuospatial performance of experienced videogamers versus *non-gamers*. Finer correlational studies compare different genres of videogames. For example, *action gamers* are usually compared to *non-action gamers*, who are players of other genres (e.g., role-playing, strategy, and logical games). These finer comparisons assume that action videogames, mostly first-person shooter games, are more demanding on perceptual and cognitive processes to foster visuospatial processing (see Spence and Feng 2010; see also Dobrowolski et al. 2015), compared to non-action videogames.

Table 6.3 Designs and conditions of research about videogames for visuospatial processing

Design	Condition
Correlational	Non-gamer
	Non-action gamer
	Action gamer
Experimental	Passive control (no training)
	Active control (computer task or easier videogame training)
	Non-action treatment (non-action videogame training)
	Action treatment (action videogame training)

The assumption is generally met, as players with experience in action games tend to show better visuospatial processing abilities than non-action gamers (e.g., Colzato et al. 2013). For example, the meta-analysis by Powers et al. (2013) showed a small-sized effect (k = 37, d = 0.27, p = .001) of videogames from different genres on cognitive tasks related to visuospatial processing. Also, the meta-analysis by Sala et al. (2018) showed an overall small effect (k = 16, g = 0.21, p = .005) of diverse videogames on spatial ability tasks.

In contrast, another meta-analysis by Sala et al. (2018), which only included action videogames, showed a medium effect size (k = 8, g = 0.47, p = .001). Similarly, Bediou et al. (2018) showed a large effect size (k = 27, g = 0.75, p < .001) in a meta-analysis including solely action videogames. These meta-analyses support that playing action videogames may contribute more in developing visuospatial processing ability, compared to playing non-action games.

Of course, the correlational findings do not indicate whether there is a causal relationship between videogaming and visuospatial skill. That is addressed by experimental designs. The typical experimental study compares the gains in visuospatial skill from pre- to post-test of two groups of unexperienced players. The treatment condition receives some amount of videogame training to improve in visuospatial tasks. As with correlational studies, there is research with either *action treatment* (action videogame training) or *non-action treatment* (non-action videogame training). As shown in Table 6.3, these treatments are commonly compared to either: (a) a *passive control* condition that did not train, and was only measured in visuospatial pre- and post-tests; or (b) an *active control* condition that trained in other activities, such as computer tasks or easier versions of the videogames. In the next subsections, we describe experiments investigating the effects of non-action (Sect. 6.3.3) and action (Sect. 6.3.4) videogames on visuospatial processing.

6.3.3 Non-action Videogames for Visuospatial Processing

Dorval and Pepin (1986) conducted a seminal experiment on the effects of non-action videogames on visuospatial processing. In their investigation, 70 non-gamer humanities undergraduates (47% females) were randomly assigned to a passive control group or the experimental group. Participants in the experimental group completed eight sessions of playing an arcade videogame in which a spaceship had to elude obstacles and shoot enemies in a 3D space. Results indicated that playing the spaceship game improved scores on a mental folding test. In contrast, the control group performed similarly in pre- and post-tests.

In a study by De Lisi and Cammarano (1996), 110 undergraduates (75% females) were randomly assigned to two different videogame training groups. In both conditions, the training involved two playing sessions of 30 min each, separated by 1 week. In the treatment group, the students played a videogame involving the rotation and placement of 3D shapes. In the active control group, the training involved playing solitaire card videogames. Results showed that the 3D shape training was significantly more effective to increase performance in the pen-and-paper Mental Rotations Test, as compared to the solitaire training.

More recently, the meta-analysis by Powers et al. (2013) showed a medium effect ($k = 77$, $d = 0.43$, $p = .001$) and the meta-analysis by Sala et al. (2018) reported a small effect size ($k = 37$, $g = 0.21$, $p = .001$) of non-action videogame training on visuospatial processing. These overall effects considered studies using different visuospatial tests, as well as different non-action videogames. However, much of the literature relating non-action videogames to visuospatial instruments has concerned Tetris™, the videogame that involves rotating 2D abstract shapes.

The research involving Tetris has yielded mixed results. In one experiment by Okagaki and Frensch (1994), 57 psychology undergraduates (51% females) inexperienced with Tetris played the game for 6 h across 12 sessions. These students were compared to a passive control group. All participants completed three pen-and-paper tests of visuospatial processing: (a) the Cube Comparisons Test (mental rotation with 3D shapes), (b) the Card Rotations Test (mental rotation with 2D shapes), and (c) the Form Board Test (mental folding). Results indicated that male students who played Tetris improved their scores on the Cube Comparisons Test and the Form Board Test. In contrast, females who played Tetris did not improve in any of the three tests.

Similarly, Moreau (2012) reported the effects of 12 h of total training (16 sessions of 45 min each) with block Tetris-type videogames. In an experiment with 46 university students (52% females), two training conditions were compared: a version using 2D Tetris shapes and a version with 3D Tetris blocks. Both conditions showed pre- to post-test improvement on other visuospatial tasks, but the 3D version yielded the strongest benefits. Specifically, the 2D game improved mental rotations on other tasks with 2D blocks and 2D human bodies but failed on tasks with 3D blocks or 3D bodies. In contrast, videogame training with 3D Tetris blocks improved mental rotations on both 3D and 2D blocks and bodies.

In contrast, other experiments have reported null effects of Tetris training. For example, a study by Sims and Mayer (2002, Experiment 2) investigated 16 female undergraduates with no previous experience in Tetris. The experiment studied improvements in visuospatial processing measured by three common pen-and-paper instruments: (a) the Card Rotations Test (2D mental rotation), (b) the Paper Folding Test (mental folding), and (c) the Form Board Test (mental folding). Participants were randomly assigned to either a passive condition without training or they trained in Tetris for 12 h (1 h sessions across 12 days). Results showed that the Tetris training did not significantly increase scores on the standard visuospatial instruments.

Comparable results were observed in two studies by Pilegard and Mayer (2018) involving undergraduate non-videogame players. The studies investigated whether Tetris training could transfer to six cognitive skills measured on computer-based tests, including four visuospatial abilities: (a) mental rotation with abstract 2D shapes (Card Rotations Test), (b) mental rotation with Tetris and Tetris-like shapes (2-D Tetris rotations), (c) mental folding (Form Board Test), and (d) spatial working memory (Corsi Block Tapping Test). The studies compared two Tetris training conditions to a passive control group. Results revealed that both training conditions—regular Tetris play and Tetris play supplemented with prompts—did not produce significant gains in any of the cognitive abilities measured.

In short, Tetris and other non-action videogames tend to show a small or null influence on visuospatial test scores. Generally, in these experiments the treatment condition was compared to passive controls that did not perform any training. A more rigorous approach is typically used in action videogame training, where the treatment condition is compared to a control group that does receive some comparable training.

6.3.4 Action Videogames for Visuospatial Processing

As reviewed by Spence and Feng (2010; see also Bediou et al. 2018), three genres of videogames are most amenable to train visuospatial processing: action, driving, and puzzle. From this group, most of the research has concentrated on action videogames, particularly on the popular first-person shooter games. Spence and Feng (2010) summarized experimental findings showing that first-person shooter videogames can activate sensory processes, attentional resources, fast coordination of hands and vision, and visuospatial working memory.

By activating these processes, playing action videogames (particularly first-person shooter games) can provide cognitively-demanding experiences that enhance visuospatial processing. For example, Green and Bavelier (2003, Experiment 5) compared two groups of adult non-gamers who received different videogame training for a total of 10 h (1 h in 10 consecutive days). The results showed that participants who trained with an action videogame improved their spatial distribution of visual attention significantly more than participants who trained with a non-action videogame. The same authors reported a later study (Green and Bavelier 2007) in which both correlational (Experiment 1, 20 male undergraduates) and experimental evidence (Experiment 2, 32 adults, 53% females) indicated that action videogame experience provided a positive boost for spatial resolution of vision. In other words, action videogame playing could help people discriminate smaller distances between visual targets and distractors.

Furthermore, Feng et al. (2007, Experiment 2) investigated the effects of 10 h of videogame training (in sessions of 1–2 h) on 20 undergraduates (70% females). Participants were randomly assigned to either play an action videogame or a non-action game. Results indicated that only training with the action videogame improved the scores of the spatial attention and mental rotation tests.

Similarly, Sanchez (2012) investigated the effects of two videogame training conditions on visuospatial processing of 60 university students (38% females). All participants completed tests of 2D mental rotation (Card Rotations Test) and mental folding (Paper Folding Test). During a 25-min training phase, half of the participants played an action first-person shooter game, whereas the other half played a verbal word-making game. The action training group outperformed the verbal-training group on the Mental Rotations Test, but there were no differences on the Paper Folding Test. Thus, visuospatial training with a first-person shooter videogame boosted 2D mental rotation performance but not mental folding.

Finally, a study by Blacker et al. (2014) involving 34 male undergraduates, compared the effects of 30 h (1 h per 30 days) of training with either an action game or a simulation game. Only the action training group significantly improved performance on a measure of visual working memory capacity. However, the effect of action training was smaller for a test of visual working memory precision, and there was no significant performance increase on a dual visuospatial task of working memory (Symmetry Span). Hence, action videogame training was effective for the less-demanding visual working memory tasks, but not for the complex dual task.

Overall, the studies reported above indicate rather positive outcomes of playing action videogames on various visuospatial processing tests. Recent meta-analyses have aggregated these findings. Although Bediou et al. (2018) observed a medium-sized effect ($k = 28$, $g = 0.44$, $p = .020$), Sala et al. (2018) reported no significant positive effect ($k = 22$, $g = 0.12$, $p = .248$) for action videogame training on cognitive tasks related to visuospatial processing. Taken together, there is some evidence that playing action videogames can enhance particular types of visuospatial skills such as 3D mental rotation.

6.4 Discussion

Among the diversity of instructional multimedia tools for the health and natural sciences, we focus in this chapter on simulations and videogames, as they allow students the highest levels of interactivity. We described interactivity as the exchange between the students' cognitive engagement and the multimedia's feedback. We followed the ICAP framework to describe student cognitive engagement as high-level (interactive and constructive) or low-level (active and passive). Similarly, feedback provided by the multimedia also ranges from high-level (explanatory) to low-level (corrective). In general, higher levels of engagement and feedback produce more meaningful learning in multimedia settings. However, as predicted by cognitive load theory, excessive engagement or feedback can be counterproductive, particularly for students with low visuospatial processing capacity. Because these students have fewer working memory resources to deal with the visualizations of simulations and videogames, they have problems simultaneously processing the learning elements plus engagement or feedback information. In short, a balanced degree of engagement and feedback should be provided to students.

Concerning simulations, we described their advantages over more traditional physical laboratory activities, although a couple of potential disadvantages were also acknowledged. We also provided evidence from various science disciplines (including anatomy, surgery, biology, and geology) supporting effective learning of these topics from simulations and virtual laboratories. Finally, we addressed that visuospatial processing abilities, such as mental rotation, were helpful to learn from simulations and complex visualizations.

Regarding videogames, we provided evidence of their positive effects on health and natural science learning, and for training visuospatial processing abilities. We consider that these two positive outcomes overpower the two potential negative results attributed to videogames (wasted time and aggressive behavior). Although there is accumulating research on the effectiveness of videogames for science learning, most of the studies have focused on the impact of videogames on visuospatial processing. We considered both correlational and experimental visuospatial research, usually comparing non-gamers to gamers of non-action (e.g., Tetris) or action (e.g., first-person shooter) videogames. We described that non-action videogames tended to show smaller effects than action videogames on visuospatial processing skills. We finished by remarking that robust evidence can be obtained by experimental studies that compare the effects of playing action videogames to the experience of performing similar activities (e.g., playing non-action videogames).

6.4.1 Instructional Implications for Health and Natural Sciences

A first instructional implication is that science simulations and videogames should be designed to foster interactive and constructive engagement by the student and explanatory feedback by the multimedia, rather than lower degrees of interactivity.

A second implication, which follows from the previous, is that higher degrees of interactivity should only provide necessary engagement and feedback, because when this information is irrelevant or unnecessary, working memory or cognitive overload may occur. This is particularly relevant for lower visuospatial processing students and interactive multimedia depicting complex visualizations or topics.

A third instructional implication is to measure visuospatial processing abilities of students, in case remedial actions are needed with the low scorers.

A fourth implication is for science simulations. Learning activities with these multimedia tools should benefit from the advantages of simulations over physical laboratories. For example, the laboratory activities in simulations could imply collecting large datasets, visualizing unobservable phenomena, or employing many reactants and equipment.

A fifth implication concerns science videogames. Acknowledging a potential negative effect of entertainment videogames for inducing a waste of time, educational science videogames should not be promoted to replace other meaningful learning activities.

The last implication is that action videogaming should be encouraged, chiefly those that do not induce aggressive behaviors. They could be beneficial to train visuospatial processing abilities in those students with low performance.

6.4.2 Future Research Directions

Future research should explore ways to design science multimedia that strike a balance between fostering high cognitive engagement (as emphasized by the ICAP framework) and managing learner's limited cognitive resources (as emphasized by cognitive load theory). If the multimedia is too cognitively demanding, such as when the learning material is highly complex, then adding more engagement or generative activities could be counterproductive (cf. Chen et al. 2018). Future research should systematically evaluate multimedia environments of different complexities and levels of engagement to test predictions derived from the ICAP framework and cognitive load theory. Furthermore, motivational, emotional, and behavioral processes should be examined for a more complete picture of the complex processes involved in learning from science multimedia (see Park et al. 2015; Plass et al. 2014; see also Fraser et al. 2012, 2015).

As visualizations and multimedia do not impact science and other disciplines (e.g., math and technology) to the same degree (e.g., Castro-Alonso et al. 2019b), future research on simulations and videogames should focus on a particular subdiscipline (e.g., biology, chemistry, technology) or compare their differences.

In addition, future endeavors should consider other students' characteristics in addition to visuospatial processing. For example, sex is a possible candidate (see Castro-Alonso and Jansen this volume, Chap. 4), as it appears to moderate the experiences of learning from visualizations (e.g., Castro-Alonso et al. 2019b; Wong et al. 2018), using computers (e.g., Drabowicz 2014), and playing videogames (e.g., Terlecki and Newcombe 2005).

From a methodological standpoint, future research should continue to increase its standards of rigor. Fiorella and Mayer (2018) observed that comparisons with well-matched control groups are those that follow a *value-added methodology*. For example, a value-added approach for simulations would go beyond comparing a simulation (experimental group) to other educational material (control group), in order to contrast two simulations that only differ in one feature or variable (see also Castro-Alonso et al. 2016). For videogames, as described by Mayer (2015), this research should follow sound research methods, such as including well-matched active control groups and randomly assigning participants to the treatment and control groups.

Also, Mayer (2017) proposed three core components of a research agenda applicable to interactive multimedia simulations and videogames: (a) investigating emerging technologies, such as virtual reality, and mobile phones; (b) conducting research in real classroom settings, which provide more ecological validity than common laboratory studies; and (c) testing the effects of interventions across longer durations, which provide more robust implications compared to shorter lab-based interventions.

Finally, beyond the scope of this chapter (and book), other visuospatial processing abilities could be considered, such as dynamic spatial abilities (e.g., Sanchez and Wiley 2014) or environmental spatial abilities (e.g., Kozhevnikov et al. 2013). Similarly, research should investigate more direct relationships between particular visuospatial abilities and particular interactive science tasks (see Castro-Alonso et al. 2019a; see also Section 3.5 in Fiorella and Mayer 2018).

6.4.3 Conclusion

Simulations and videogames allow students the highest levels of information exchanges, in which engagement from the students is followed by feedback from the multimedia. Although this high interactivity is usually positive, excessive engagement and feedback can also be negative, especially for low visuospatial capacity learners, as they cannot process the learning elements plus the extra interactive features. Properly designed simulations and videogames, which find a balance in the degree of interactivity, have proven to be effective instructional tools for topics about health and natural sciences. In addition to being effective for science learning, these multimedia products have also shown a positive relationship with visuospatial processing. Most of this research has focused on videogames (e.g., action videogames) and their positive effect on training visuospatial skills. Future research will help in providing greater details on the type of visuospatial processing ability most needed for certain tasks or topics involving science simulations and videogames.

Acknowledgments Support from PIA–CONICYT Basal Funds for Centers of Excellence Project FB0003 is gratefully acknowledged. The first author is thankful to Mariana Poblete for her assistance, and to Ignacio Jarabran for helping with the simulation and videogame illustrations.

References

Adam, K. C. S., & Vogel, E. K. (2018). Improvements to visual working memory performance with practice and feedback. *PLoS One, 13*(8), e0203279. https://doi.org/10.1371/journal.pone.0203279.

Allen, L. K., Eagleson, R., & de Ribaupierre, S. (2016). Evaluation of an online three-dimensional interactive resource for undergraduate neuroanatomy education. *Anatomical Sciences Education, 9*(5), 431–439. https://doi.org/10.1002/ase.1604.

Anderson, J., & Barnett, M. (2011). Using video games to support pre-service elementary teachers learning of basic physics principles. *Journal of Science Education and Technology, 20*(4), 347–362. https://doi.org/10.1007/s10956-010-9257-0.

Barrett, T. J., Stull, A. T., Hsu, T. M., & Hegarty, M. (2015). Constrained interactivity for relating multiple representations in science: When virtual is better than real. *Computers & Education, 81*, 69–81. https://doi.org/10.1016/j.compedu.2014.09.009.

Bediou, B., Adams, D. M., Mayer, R. E., Tipton, E., Green, C. S., & Bavelier, D. (2018). Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychological Bulletin, 144*(1), 77–110. https://doi.org/10.1037/bul0000130.

Blackburn, R. A. R., Villa-Marcos, B., & Williams, D. P. (2019). Preparing students for practical sessions using laboratory simulation software. *Journal of Chemical Education, 96*(1), 153–158. https://doi.org/10.1021/acs.jchemed.8b00549.

Blacker, K. J., Curby, K. M., Klobusicky, E., & Chein, J. M. (2014). Effects of action video game training on visual working memory. *Journal of Experimental Psychology: Human Perception & Performance, 40*(5), 1992–2004. https://doi.org/10.1037/a0037556.

Bonde, M. T., Makransky, G., Wandall, J., Larsen, M. V., Morsing, M., Jarmer, H., et al. (2014). Improving biotech education through gamified laboratory simulations. *Nature Biotechnology, 32*(7), 694–697. https://doi.org/10.1038/nbt.2955.

Boyle, E. A., Hainey, T., Connolly, T. M., Gray, G., Earp, J., Ott, M., et al. (2016). An update to the systematic literature review of empirical evidence of the impacts and outcomes of computer games and serious games. *Computers & Education, 94*, 178–192. https://doi.org/10.1016/j.compedu.2015.11.003.

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education, 87*, 218–237. https://doi.org/10.1016/j.compedu.2015.07.003.

Castro-Alonso, J. C., & Atit, K. (this volume). Different abilities controlled by visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 23–51). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_2.

Castro-Alonso, J. C., & Jansen, P. (this volume). Sex differences in visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 81–110). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_4.

Castro-Alonso, J. C., & Uttal, D. H. (2019). Spatial ability for university biology education. In S. Nazir, A.-M. Teperi, & A. Polak-Sopińska (Eds.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2018 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 283–291). Cham: Springer. https://doi.org/10.1007/978-3-319-93882-0_28.

Castro-Alonso, J. C., & Uttal, D. H. (this volume). Science education and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 53–79). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_3.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015). The potential of embodied cognition to improve STEAM instructional dynamic visualizations. In X. Ge, D. Ifenthaler, & J. M. Spector (Eds.), *Emerging technologies for STEAM education: Full STEAM ahead* (pp. 113–136). New York: Springer. https://doi.org/10.1007/978-3-319-02573-5_7.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2016). Comparing apples and oranges? A critical look at research on learning from statics versus animations. *Computers & Education, 102*, 234–243. https://doi.org/10.1016/j.compedu.2016.09.004.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018). Computerized and adaptable tests to measure visuospatial abilities in STEM students. In T. Andre (Ed.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2017 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 337–349). Cham: Springer. https://doi.org/10.1007/978-3-319-60018-5_33.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2019a). Visuospatial tests and multimedia learning: The importance of employing relevant instruments. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (pp. 89–99). New York: Routledge. https://doi.org/10.4324/9780429283895-8.

Castro-Alonso, J. C., Wong, M., Adesope, O. O., Ayres, P., & Paas, F. (2019b). Gender imbalance in instructional dynamic versus static visualizations: A meta-analysis. *Educational Psychology Review*, *31*(2), 361–387. https://doi.org/10.1007/s10648-019-09469-1.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (this volume-a). VAR: A battery of computer-based instruments to measure visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 207–229). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_8.

Castro-Alonso, J. C., Ayres, P., & Sweller, J. (this volume-b). Instructional visualizations, cognitive load theory, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 111–143). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_5.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (this volume-c). Embodied cognition, science education, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 175–205). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_7.

Chen, O., Castro-Alonso, J. C., Paas, F., & Sweller, J. (2018). Undesirable difficulty effects in the learning of high-element interactivity materials. *Frontiers in Psychology, 9*, 1483), 1–1483), 7. https://doi.org/10.3389/fpsyg.2018.01483.

Cheng, M.-T., Su, T., Huang, W.-Y., & Chen, J.-H. (2014). An educational game for learning human immunology: What do students learn and how do they perceive? *British Journal of Educational Technology, 45*(5), 820–833. https://doi.org/10.1111/bjet.12098.

Cheng, M.-T., Chen, J.-H., Chu, S.-J., & Chen, S.-Y. (2015). The use of serious games in science education: A review of selected empirical research from 2002 to 2013. *Journal of Computers in Education, 2*(3), 353–375. https://doi.org/10.1007/s40692-015-0039-9.

Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: Linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*(4), 219–243. https://doi.org/10.1080/00461520.2014.965823.

Clark, D. B., Tanner-Smith, E. E., & Killingsworth, S. S. (2016). Digital games, design, and learning: A systematic review and meta-analysis. *Review of Educational Research, 86*(1), 79–122. https://doi.org/10.3102/0034654315582065.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale: Erlbaum.

Colzato, L. S., van den Wildenberg, W. P. M., Zmigrod, S., & Hommel, B. (2013). Action video gaming and cognitive control: Playing first person shooter games is associated with improvement in working memory but not action inhibition. *Psychological Research, 77*(2), 234–239. https://doi.org/10.1007/s00426-012-0415-2.

Cummings, H. M., & Vandewater, E. A. (2007). Relation of adolescent video game play to time spent in other activities. *Archives of Pediatrics & Adolescent Medicine, 161*(7), 684–689. https://doi.org/10.1001/archpedi.161.7.684.

De Lisi, R., & Cammarano, D. M. (1996). Computer experience and gender differences in undergraduate mental rotation performance. *Computers in Human Behavior, 12*(3), 351–361. https://doi.org/10.1016/0747-5632(96)00013-1.

Dobrowolski, P., Hanusz, K., Sobczyk, B., Skorko, M., & Wiatrow, A. (2015). Cognitive enhancement in video game players: The role of video game genre. *Computers in Human Behavior, 44*, 59–63. https://doi.org/10.1016/j.chb.2014.11.051.

Domagk, S., Schwartz, R. N., & Plass, J. L. (2010). Interactivity in multimedia learning: An integrated model. *Computers in Human Behavior, 26*(5), 1024–1033. https://doi.org/10.1016/j.chb.2010.03.003.

Donovan, L. M., Argenbright, C. A., Mullen, L. K., & Humbert, J. L. (2018). Computer-based simulation: Effective tool or hindrance for undergraduate nursing students? *Nurse Education Today, 69*, 122–127. https://doi.org/10.1016/j.nedt.2018.07.007.

Dorval, M., & Pepin, M. (1986). Effect of playing a video game on a measure of spatial visualization. *Perceptual and Motor Skills, 62*(1), 159–162. https://doi.org/10.2466/pms.1986.62.1.159.

Drabowicz, T. (2014). Gender and digital usage inequality among adolescents: A comparative study of 39 countries. *Computers & Education, 74*, 98–111. https://doi.org/10.1016/j.compedu.2014.01.016.

Erhel, S., & Jamet, E. (2006). Using pop-up windows to improve multimedia learning. *Journal of Computer Assisted Learning, 22*(2), 137–147. https://doi.org/10.1111/j.1365-2729.2006.00165.x.

Evans, C., & Gibbons, N. J. (2007). The interactivity effect in multimedia learning. *Computers & Education, 49*(4), 1147–1160. https://doi.org/10.1016/j.compedu.2006.01.008.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science, 18*(10), 850–855. https://doi.org/10.1111/j.1467-9280.2007.01990.x.

Ferguson, C. J. (2007). The good, the bad and the ugly: A meta-analytic review of positive and negative effects of violent video games. *Psychiatric Quarterly, 78*(4), 309–316. https://doi.org/10.1007/s11126-007-9056-9.

Ferguson, C. J. (2010). Blazing angels or resident evil? Can violent video games be a force for good? *Review of General Psychology, 14*(2), 68–81. https://doi.org/10.1037/a0018941.

Fiorella, L., & Mayer, R. E. (2012). Paper-based aids for learning with a computer-based game. *Journal of Educational Psychology, 104*(4), 1074–1082. https://doi.org/10.1037/a0028088.

Fiorella, L., & Mayer, R. E. (2015). *Learning as a generative activity: Eight learning strategies that promote understanding*. New York: Cambridge University Press.

Fiorella, L., & Mayer, R. E. (2016). Eight ways to promote generative learning. *Educational Psychology Review, 28*(4), 717–741. https://doi.org/10.1007/s10648-015-9348-9.

Fiorella, L., & Mayer, R. E. (2018). What works and doesn't work with instructional video. *Computers in Human Behavior, 89*, 465–470. https://doi.org/10.1016/j.chb.2018.07.015.

Fiorella, L., Vogel-Walcutt, J. J., & Fiore, S. (2012a). Differential impact of two types of metacognitive prompting provided during simulation-based training. *Computers in Human Behavior, 28*(2), 696–702. https://doi.org/10.1016/j.chb.2011.11.017.

Fiorella, L., Vogel-Walcutt, J. J., & Schatz, S. (2012b). Applying the modality principle to real-time feedback and the acquisition of higher-order cognitive skills. *Educational Technology Research and Development, 60*(2), 223–238. https://doi.org/10.1007/s11423-011-9218-1.

Fraser, K. L., Ma, I., Teteris, E., Baxter, H., Wright, B., & McLaughlin, K. (2012). Emotion, cognitive load and learning outcomes during simulation training. *Medical Education, 46*(11), 1055–1062. https://doi.org/10.1111/j.1365-2923.2012.04355.x.

Fraser, K. L., Ayres, P., & Sweller, J. (2015). Cognitive load theory for the design of medical simulations. *Simulation in Healthcare, 10*(5), 295–307. https://doi.org/10.1097/sih.0000000000000097.

Garg, A. X., Norman, G., & Sperotable, L. (2001). How medical students learn spatial anatomy. *The Lancet, 357*(9253), 363–364. https://doi.org/10.1016/S0140-6736(00)03649-7.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature, 423*(6939), 534–537.

Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological Science, 18*(1), 88–94. https://doi.org/10.1111/j.1467-9280.2007.01853.x.

Hartanto, A., Toh, W. X., & Yang, H. (2018). Context counts: The different implications of weekday and weekend video gaming for academic performance in mathematics, reading, and science. *Computers & Education, 120*, 51–63. https://doi.org/10.1016/j.compedu.2017.12.007.

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of Educational Research, 77*(1), 81–112. https://doi.org/10.3102/003465430298487.

Hilgard, J., Engelhardt, C. R., Rouder, J. N., Segert, I. L., & Bartholow, B. D. (2019). Null effects of game violence, game difficulty, and 2D: 4D digit ratio on aggressive behavior. *Psychological Science, 30*(4), 606-616. https://doi.org/10.1177/0956797619829688.

Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. *Journal of Computer Assisted Learning, 22*(6), 392–404. https://doi.org/10.1111/j.1365-2729.2006.00180.x.

Huk, T., & Steinke, M. (2007). Learning cell biology with close-up views or connecting lines: Evidence for the structure mapping effect. *Computers in Human Behavior, 23*(3), 1089–1104. https://doi.org/10.1016/j.chb.2006.10.004.

Ilgen, J. S., Sherbino, J., & Cook, D. A. (2013). Technology-enhanced simulation in emergency medicine: A systematic review and meta-analysis. *Academic Emergency Medicine, 20*(2), 117–127. https://doi.org/10.1111/acem.12076.

Johnson, C. I., & Priest, H. A. (2014). The feedback principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 449–463). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.023.

Johnson, C. I., Bailey, S. K. T., & Van Buskirk, W. L. (2017). Designing effective feedback messages in serious games and simulations: A research review. In P. Wouters & H. van Oostendorp (Eds.), *Instructional techniques to facilitate learning and motivation of serious games* (pp. 119–140). Cham: Springer. https://doi.org/10.1007/978-3-319-39298-1_7.

Kalet, A. L., Song, H. S., Sarpel, U., Schwartz, R. N., Brenner, J., Ark, T. K., et al. (2012). Just enough, but not too much interactivity leads to better clinical skills performance after a computer assisted learning module. *Medical Teacher, 34*(10), 833–839. https://doi.org/10.3109/0142159X.2012.706727.

Karich, A. C., Burns, M. K., & Maki, K. E. (2014). Updated meta-analysis of learner control within educational technology. *Review of Educational Research, 84*(3), 392–410. https://doi.org/10.3102/0034654314526064.

Keehner, M., Lippa, Y., Montello, D. R., Tendick, F., & Hegarty, M. (2006). Learning a spatial skill for surgery: How the contributions of abilities change with practice. *Applied Cognitive Psychology, 20*(4), 487–503. https://doi.org/10.1002/acp.1198.

Keehner, M., Hegarty, M., Cohen, C., Khooshabeh, P., & Montello, D. R. (2008). Spatial reasoning with external visualizations: What matters is what you see, not whether you interact. *Cognitive Science, 32*(7), 1099–1132. https://doi.org/10.1080/03640210801898177.

Klahr, D., Triona, L. M., & Williams, C. (2007). Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children. *Journal of Research in Science Teaching, 44*(1), 183–203. https://doi.org/10.1002/tea.20152.

Kostusiak, M., Hart, M., Barone, D. G., Hofmann, R., Kirollos, R., Santarius, T., et al. (2017). Methodological shortcomings in the literature evaluating the role and applications of 3D training for surgical trainees. *Medical Teacher, 39*(11), 1168–1173. https://doi.org/10.1080/0142159X.2017.1362102.

Kozhevnikov, M., Schloerb, D. W., Blazhenkova, O., Koo, S., Karimbux, N., Donoff, R. B., et al. (2013). Egocentric versus allocentric spatial ability in dentistry and haptic virtual reality training. *Applied Cognitive Psychology, 27*(3), 373–383. https://doi.org/10.1002/acp.2915.

Lin, J.-H. (2013). Do video games exert stronger effects on aggression than film? The role of media interactivity and identification on the association of violent content and aggressive outcomes. *Computers in Human Behavior, 29*(3), 535–543. https://doi.org/10.1016/j.chb.2012.11.001.

Lin, L., & Li, M. (2018). Optimizing learning from animation: Examining the impact of biofeedback. *Learning and Instruction, 55*, 32–40. https://doi.org/10.1016/j.learninstruc.2018.02.005.

Loftus, J. J., Jacobsen, M., & Wilson, T. D. (2017). Learning and assessment with images: A view of cognitive load through the lens of cerebral blood flow. *British Journal of Educational Technology, 48*(4), 1030–1046. https://doi.org/10.1111/bjet.12474.

Low, R., & Sweller, J. (2014). The modality principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 227–246). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.012.

Lynch, J., Aughwane, P., & Hammond, T. M. (2010). Video games and surgical ability: A literature review. *Journal of Surgical Education, 67*(3), 184–189. https://doi.org/10.1016/j.jsurg.2010.02.010.

Mayer, R. E. (2014). Introduction to multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 1–24). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.002.

Mayer, R. E. (2015). On the need for research evidence to guide the design of computer games for learning. *Educational Psychologist, 50*(4), 349–353. https://doi.org/10.1080/00461520.2015.1133307.

Mayer, R. E. (2017). Using multimedia for e-learning. *Journal of Computer Assisted Learning, 33*(5), 403–423. https://doi.org/10.1111/jcal.12197.

Mayer, R. E. (2019). Computer games in education. *Annual Review of Psychology, 70*, 531–549. https://doi.org/10.1146/annurev-psych-010418-102744.

Mayer, R. E., & Fiorella, L. (2014). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 279–315). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.015.

Miranda, A. T., & Palmer, E. M. (2014). Intrinsic motivation and attentional capture from game-like features in a visual search task. *Behavior Research Methods, 46*(1), 159–172. https://doi.org/10.3758/s13428-013-0357-7.

Moreau, D. (2012). Differentiating two- from three-dimensional mental rotation training effects. *The Quarterly Journal of Experimental Psychology, 66*(7), 1399–1413. https://doi.org/10.1080/17470218.2012.744761.

Moreno, R. (2004). Decreasing cognitive load for novice students: Effects of explanatory versus corrective feedback in discovery-based multimedia. *Instructional Science, 32*(1–2), 99–113. https://doi.org/10.1023/B:TRUC.0000021811.66966.1d.

Moreno, R., & Mayer, R. E. (2005). Role of guidance, reflection, and interactivity in an agent-based multimedia game. *Journal of Educational Psychology, 97*(1), 117–128. https://doi.org/10.1037/0022-0663.97.1.117.

Moreno, R., & Mayer, R. (2007). Interactive multimodal learning environments. *Educational Psychology Review, 19*(3), 309–326. https://doi.org/10.1007/s10648-007-9047-2.

Nicholson, D. T., Chalk, C., Funnell, W. R. J., & Daniel, S. J. (2006). Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model. *Medical Education, 40*(11), 1081–1087. https://doi.org/10.1111/j.1365-2929.2006.02611.x.

Okagaki, L., & Frensch, P. A. (1994). Effects of video game playing on measures of spatial performance: Gender effects in late adolescence. *Journal of Applied Developmental Psychology, 15*(1), 33–58. https://doi.org/10.1016/0193-3973(94)90005-1.

Park, B., Knörzer, L., Plass, J. L., & Brünken, R. (2015). Emotional design and positive emotions in multimedia learning: An eye tracking study on the use of anthropomorphisms. *Computers & Education, 86*, 30–42. https://doi.org/10.1016/j.compedu.2015.02.016.

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology, 110*(6), 785–797. https://doi.org/10.1037/edu0000241.

Piburn, M. D., Reynolds, S. J., McAuliffe, C., Leedy, D. E., Birk, J. P., & Johnson, J. K. (2005). The role of visualization in learning from computer-based images. *International Journal of Science Education, 27*(5), 513–527. https://doi.org/10.1080/09500690412331314478.

Pilegard, C., & Mayer, R. E. (2018). Game over for Tetris as a platform for cognitive skill training. *Contemporary Educational Psychology, 54*, 29–41. https://doi.org/10.1016/j.cedpsych.2018.04.003.

Plass, J. L., & Schwartz, R. N. (2014). Multimedia learning with simulations and microworlds. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 729–761). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.036.

Plass, J. L., Heidig, S., Hayward, E. O., Homer, B. D., & Um, E. (2014). Emotional design in multimedia learning: Effects of shape and color on affect and learning. *Learning and Instruction, 29*, 128–140. https://doi.org/10.1016/j.learninstruc.2013.02.006.

Plass, J. L., Homer, B. D., & Kinzer, C. K. (2015). Foundations of game-based learning. *Educational Psychologist, 50*(4), 258–283. https://doi.org/10.1080/00461520.2015.1122533.

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., et al. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education, 95*, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002.

Powers, K. L., Brooks, P. J., Aldrich, N. J., Palladino, M. A., & Alfieri, L. (2013). Effects of video-game play on information processing: A meta-analytic investigation. *Psychonomic Bulletin & Review, 20*(6), 1055–1079. https://doi.org/10.3758/s13423-013-0418-z.

Rivière, E., Saucier, D., Lafleur, A., Lacasse, M., & Chiniara, G. (2018). Twelve tips for efficient procedural simulation. *Medical Teacher, 40*(7), 743–751. https://doi.org/10.1080/0142159X.2017.1391375.

Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education, 58*(1), 136–153. https://doi.org/10.1016/j.compedu.2011.07.017.

Sala, G., Tatlidil, K. S., & Gobet, F. (2018). Video game training does not enhance cognitive ability: A comprehensive meta-analytic investigation. *Psychological Bulletin, 144*(2), 111–139. https://doi.org/10.1037/bul0000139.

Sanchez, C. A. (2012). Enhancing visuospatial performance through video game training to increase learning in visuospatial science domains. *Psychonomic Bulletin & Review, 19*(1), 58–65. https://doi.org/10.3758/s13423-011-0177-7.

Sanchez, C. A., & Wiley, J. (2014). The role of dynamic spatial ability in geoscience text comprehension. *Learning and Instruction, 31*, 33–45. https://doi.org/10.1016/j.learninstruc.2013.12.007.

Schwartz, R. N., & Plass, J. L. (2014). Click versus drag: User-performed tasks and the enactment effect in an interactive multimedia environment. *Computers in Human Behavior, 33*, 242–255. https://doi.org/10.1016/j.chb.2014.01.012.

Sims, V. K., & Mayer, R. E. (2002). Domain specificity of spatial expertise: The case of video game players. *Applied Cognitive Psychology, 16*(1), 97–115. https://doi.org/10.1002/acp.759.

Smetana, L. K., & Bell, R. L. (2011). Computer simulations to support science instruction and learning: A critical review of the literature. *International Journal of Science Education, 34*(9), 1337–1370. https://doi.org/10.1080/09500693.2011.605182.

Song, H. S., Pusic, M., Nick, M. W., Sarpel, U., Plass, J. L., & Kalet, A. L. (2014). The cognitive impact of interactive design features for learning complex materials in medical education. *Computers & Education, 71*, 198–205. https://doi.org/10.1016/j.compedu.2013.09.017.

Spence, I., & Feng, J. (2010). Video games and spatial cognition. *Review of General Psychology, 14*(2), 92–104. https://doi.org/10.1037/a0019491.

Stull, A. T., & Mayer, R. E. (2007). Learning by doing versus learning by viewing: Three experimental comparisons of learner-generated versus author-provided graphic organizers. *Journal of Educational Psychology, 99*(4), 808–820. https://doi.org/10.1037/0022-0663.99.4.808.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York: Springer.

Terlecki, M. S., & Newcombe, N. S. (2005). How important is the digital divide? The relation of computer and videogame usage to gender differences in mental rotation ability. *Sex Roles, 53*(5–6), 433–441. https://doi.org/10.1007/s11199-005-6765-0.

Tobias, S., Fletcher, J. D., Bediou, B., Wind, A. P., & Chen, F. (2014). Multimedia learning with computer games. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 762–784). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.037.

Triona, L. M., & Klahr, D. (2003). Point and click or grab and heft: Comparing the influence of physical and virtual instructional materials on elementary school students' ability to design experiments. *Cognition and Instruction, 21*(2), 149–173.

Urhahne, D., Nick, S., & Schanze, S. (2009). The effect of three-dimensional simulations on the understanding of chemical structures and their properties. *Research in Science Education, 39*(4), 495–513. https://doi.org/10.1007/s11165-008-9091-z.

Van der Kleij, F. M., Feskens, R. C. W., & Eggen, T. J. H. M. (2015). Effects of feedback in a computer-based learning environment on students' learning outcomes: A meta-analysis. *Review of Educational Research, 85*(4), 475–511. https://doi.org/10.3102/0034654314564881.

Weis, R., & Cerankosky, B. C. (2010). Effects of video-game ownership on young boys' academic and behavioral functioning: A randomized, controlled study. *Psychological Science, 21*(4), 463–470. https://doi.org/10.1177/0956797610362670.

Wiley, J. (2019). Picture this! Effects of photographs, diagrams, animations, and sketching on learning and beliefs about learning from a geoscience text. *Applied Cognitive Psychology, 33*(1), 9–19. https://doi.org/10.1002/acp.3495.

Wong, M., Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018). Investigating gender and spatial measurements in instructional animation research. *Computers in Human Behavior, 89*, 446–456. https://doi.org/10.1016/j.chb.2018.02.017.

Wouters, P., & van Oostendorp, H. (Eds.). (2017). *Instructional techniques to facilitate learning and motivation of serious games* (Advances in game-based learning). Cham: Springer. https://doi.org/10.1007/978-3-319-39298-1.

Chapter 7
Embodied Cognition, Science Education, and Visuospatial Processing

Juan C. Castro-Alonso, Fred Paas, and Paul Ginns

Embodied cognition, also known as *distributed* or *grounded cognition*, posits that cognition does not occur solely in the brain, but that it also employs the rest of the body and the environment (see Barsalou 2008). In other words, the mind is *extended* beyond the boundaries of the head (Clark and Chalmers 1998). This implies that the capacity limits of working memory and its visuospatial processing components (see Castro-Alonso and Atit this volume, Chap. 2) can also be extended to the body and the environment.

This extension of the mind has been investigated by cognitive load theory, the instructional theory that considers the limitations of working memory and visuospatial processing for learning (see Castro-Alonso et al. this volume-b, Chap. 5). As proposed by Choi et al. (2014), a new model of cognitive load theory can include now the new limits set by the body and the environment, and must consider body and environmental variables that could affect learning.

When the three agents—brain, body, and environment—act together, usually a boost in learning is produced. For example, Kiefer and Trumpp (2012) reviewed diverse embodied activities that led to enhanced cognition for processes such as reading and writing, processing numbers, memorizing concepts and objects, and remembering events. Among the diversity of embodied activities, we focus here on object manipulations and gestures.

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

F. Paas
Department of Psychology, Education, and Child Studies, Erasmus University Rotterdam, Rotterdam, The Netherlands

School of Education/Early Start, University of Wollongong, Wollongong, Australia

P. Ginns
Sydney School of Education and Social Work, University of Sydney, Sydney, Australia

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_7

Table 7.1 Phenomena that predict positive effects of embodiment on learning

Category	Research perspective	Example
Executing body actions	Offloaded cognition	Gesturing for mental rotations
	Generative learning	Drawing graphs or structures
	Physical activity	Training a sport (e.g., wrestling)
Executing or observing body actions	Survival cognition	Object location task for survival
	Social cognition	Mentally rotating human shapes
	Signaling	Finger pointing for memorizing

This chapter has three main aims: (a) to provide different research perspectives explaining the positive effects of embodied cognition on learning and visuospatial processing (Sects. 7.1, 7.2 and 7.3); (b) to describe various investigations relating object manipulation to education in sciences and visuospatial processing (Sect. 7.4); and (c) to give examples of studies that show a positive relationship between gesturing, science learning, and visuospatial processing (Sect. 7.5). Most of the visuospatial instruments and abilities described in this chapter are detailed in Castro-Alonso and Atit (this volume, Chap. 2) and in Castro-Alonso et al. (this volume-a, Chap. 8).

Regarding the first aim of the chapter, various non-mutually exclusive phenomena predict positive effects of embodiment and body actions on learning. We have grouped these phenomena into effects that are triggered: (a) solely by learners executing the actions, and (b) by learners executing the actions or learners observing others (e.g., instructors and peers) executing the actions. These perspectives and examples are summarized in Table 7.1 and described next.

7.1 Executing Body Actions

We consider three research perspectives that have investigated the positive effects on cognition triggered by executing body actions: (a) *offloaded cognition*, (b) *generative learning*, and (c) *physical activity*. These three areas tend to overlap sometimes. For example, when reviewing the learning effects of taking notes, R. S. Jansen et al. (2017) remarked that these body actions shared external storage and encoding benefits, which are, respectively, related to the offloaded cognition and generative learning that we describe next. We also include in this section the positive effects that physical activity has on cognitive processes.

7.1.1 Offloaded Cognition

As reviewed by Risko and Gilbert (2016), the two embodied mechanisms to offload cognitive activity in the brain involve placing the cognitive demands *onto-the-body* or *into-the-world*. An example of the former, in which the body is used to help processing the task, is typically observed in difficult mental rotations, in which tilting the head can reduce the degrees needed for the rotations in the mind. An example of the latter, in which the environment helps processing the task, can be observed in mental folding tasks, in which drawing sketches can help getting the correct solutions. Usually, both body and environment are involved together in offloading cognition, as the following examples with object manipulation and gestures show.

Regarding manipulations, the experiment by Vallée-Tourangeau et al. (2016) compared mental arithmetic performance of 52 psychology undergraduates and postgraduates (87% females) in two conditions of different embodiment. The *embodied* condition presented number tokens to the participants, which could be manipulated during the mental calculations. In the *non-embodied* condition, the participants had their hands palm down and still on the table. Results showed that, in the groups with reduced total working memory through articulatory suppression (mental repetition of a short word), the embodied condition was more efficient (more accuracy and fewer errors) than the non-embodied groups. In other words, the interference that reduced working memory was less problematic when the participants could manipulate the number tokens. Arguably, by offloading the arithmetic task to the body and the environment with manipulative tokens, the participants could manage with the few working more resources left due to articulatory suppression.

An example with gesturing for health science tasks is provided by Macken and Ginns (2014), who investigated 42 adults (74% females) studying illustrations and texts about the structure and function of the human heart. Half of the participants were instructed to gesture while studying (e.g., using the finger to make connections between illustrations and texts), and the other half, the control group, did not gesture. Results showed that the gesture condition outperformed the non-gesture group on a retention test of terminology and a test of comprehension. Ginns and Kydd (2019) replicated this study with 30 adults (67% females), finding the gesture condition again outperformed the non-gesture condition on both the retention and comprehension tests, while also reporting the lesson as less difficult.

Hegarty and Steinhoff (1997) provide an example of physics instruction where cognitive processing was offloaded to the environment by note-taking. In two experiments with a total of 186 undergraduates, the author investigated the instructional effects of making notes on diagrams showing the mechanics of pulley, gear, and lever systems. Mental folding of the participants was assessed with the Paper Folding Test, and the scores were used to perform a median split between low and high mental folding students. For low visuospatial processing participants, it was observed that making notes on the diagrams allowed better results. In other words, the limitations that low mental folders had to process the physics displays were compensated by them being allowed to make notes that acted as scaffolds to understand the visualizations. In contrast, high mental folders were not benefited by this note-making process. For these high visuospatial processing students, their cognitive capacity was enough to cope with the challenging learning visualizations, so they were not helped by offloading cognition into notes.

In contrast to these supporting evidence for offloaded cognition, there is also a negative side when we rely on external devices for our cognitive processes, as it has been shown for visual memory. For example, Henkel (2014, Experiment 1) investigated how taking photos of objects in an art museum affected the memory for them. In the study, the 27 undergraduates (78% females) either took photographs of 15 museum pieces (e.g., painting, pottery, sculptures) or just observed other 15 pieces. The next day, the memory test showed that the photographed objects were less remembered and with less detail than the observed pieces that were not recorded. Thus, when the participants relied on offloading cognition to the environment (camera), they used less effectively their own cognition to memorize the items (see also the review by Marsh and Rajaram 2019).

7.1.2 Generative Learning

As reviewed by Wittrock (1989), generative cognitive processes involve relating the learning contents to personal knowledge, beliefs, and experience. In other words, the students actively construct meaning from the contents and make them personal. Instructors can teach students several methods to construct this personal meaning. For example, to understand better a text passage, Wittrock (1989) recommended students' actions such as writing personal questions or summaries, giving examples, and drawing own graphs or pictures.

It can be noted that these actions also involve offloading cognition. The critical addition is that generative actions are personal and original actions. For example, although writing a question can offload cognition to the environment, it only becomes a generative learning example when the question is personal rather than a copy from the teacher.

To the list of actions by Wittrock (1989), Fiorella and Mayer (2016b) added the activities of summarizing and taking notes (see also R. S. Jansen et al. 2017), self-explaining (see also Chi et al. 1994), imagining (see also Ginns et al. 2003), preparing to teach and teaching (see also Fiorella and Mayer 2013; Hoogerheide et al. 2019), and enacting. From this diversity of generative actions, the focus of this chapter is on enacting, chiefly manipulation and gestures. However, in this section we consider the action of drawing, as it is a highly visuospatial generative activity.

Study 1 in Fiorella and Mayer (2017) investigated 108 undergraduates (70% females) drawing maps and illustrations to understand better a biology text about the human respiratory system. Also, students' visuospatial processing was calculated averaging the scores of: (a) the Cube Comparisons Test, a common mental rotation test with three-dimensional (3D) shapes; and (b) the Paper Folding Test, a typical instrument of mental folding (see about these tests in Castro-Alonso and Atit this volume, Chap. 2). Results showed that both the spatial generative strategies and visuospatial processing independently predicted effective learning from the scientific text. Similarly, in an experiment with 72 undergraduates learning chemistry from a multimedia module, S. P. W. Wu and Rau (2018) reported the effects of drawing chemical structures on paper while studying from the computers. Results showed that the conditions in which the program prompted the students to draw were more efficient (higher learning performance per time on task) than the condition without these illustration prompts. Similarly, when 120 undergraduates (64% females) were randomly assigned to study a geoscience text in different learning conditions, Wiley (2019) observed that the best performance was on the group instructed to sketch the contents.

Nevertheless, generative activities are not always productive for learning. As predicted by cognitive load theory (see Sweller et al. 2011; see also Castro-Alonso et al. this volume-b, Chap. 5), since working memory is limited, when generative activity involves too much working memory processing, this cognitive processing may interfere with learning. This is noticeable when the learning materials are complex for the students. For example, Ploetzner and Fillisch (2017) investigated 52 undergraduates (83% females) studying a complex animation about a four-stroke engine. The participants were randomly assigned to drawing or reflecting what they observed in the animation. Findings revealed that the overall structures were less frequently recognized in the drawing condition than in the reflection group. Also, in three experiments with a total of 370 university participants (66% females), Stull and Mayer (2007) compared students building concept maps about the reproductive barriers between species, versus conditions where the maps were already completed. A consistent finding of the three experiments was that the generative actions of building the maps were counterproductive to learning the biology topic. In short, instructors and teachers should pursue balanced learning activities, where generative actions are included in a quantity that is sufficient and not excessive.

7.1.3 Physical Activity

Pothier and Bherer (2016) defined *physical activity* as body movements by skeletal muscles using energy. This activity includes aerobic training, resistance training, dance, yoga, and tai chi, among others. These diverse embodied activities tend to show positive effects on cognition (Pothier and Bherer 2016). For example, Fenesi et al. (2018) investigated 77 undergraduates (78% females) studying a 50-min video lecture about the perception of forms. The students were randomly assigned to one of three groups. The *exercise breaks* condition performed three 5-minute breaks involving gross motor movements exercises (e.g., high knees, heeltaps, and jumping jacks). The *non-exercise breaks* condition performed three 5-minute breaks playing a puzzle videogame. The *control* condition studied the lecture continuously without breaks. A manipulation check revealed that the exercises increased the heart rate to approximately 70% of the maximum for young adults, indicating that the exercises were vigorous. The main results showed that the group doing breaks with exercises outperformed the non-exercise breaks groups and the control condition, on both attention and memory scores.

Exercising and sports can be productive also for visuospatial processing, in which the type of activity is important. In a study by Moreau et al. (2012), 62 undergraduate students (42% females) attempted the 3D Mental Rotations Tests. Subsequently, the participants completed sport training sessions of 2 h, weekly, for a total of 10 months. Half of the participants trained in wrestling, while the other half trained in running. Results showed that the improvements on the Mental Rotations Test after the sports training were significantly higher for wrestling compared to running. These findings indicate that not any type of physical activity is equally influential on cognition and visuospatial processing.

Note that the physical activity does not need to involve vigorous exercising or strenuous training sessions. Physical activity that positively influences cognitive processes can also be less energetically demanding, as the examples of manipulations and gestures show on science education and visuospatial processing (see Sects. 7.4 and 7.5). For another piece of evidence, Oppezzo and Schwartz (2014) reported that walking showed positive effects on the creative thinking of university students.

In addition, the effects of physical activities on visuospatial processing can be long-lasting. For example, the meta-analysis of 33 samples and 62 effect sizes by Voyer and Jansen (2017), revealed that athletes and musicians outperformed in spatial ability the subjects without these motoric experiences. The overall effect size was of $d = 0.38$. According to the behavioral sciences benchmarks by Cohen (1988), this number represents a small to medium effect size. Although this is correlational evidence, it supports that the training of motor skills that music and sport disciplines entail may positively influence visuospatial processing for long periods (but see P. Jansen et al. 2016).

7.2 Executing or Observing Body Actions

In addition to solely executing body actions, observing them can also trigger embodied mechanisms productive for learning and visuospatial processing. These observation and imitation mechanisms (e.g., Cracco et al. 2018) are partially triggered by *mirror neurons*. In arguably the first evidence of these neurons in humans, Fadiga et al. (1995) recorded the excitability of forearm and hand muscles of 12 adult participants. Results showed that the patterns of muscle activation were very similar during the execution of an action and observation of the same action done by another person. Later evidence has supported that these neurons constitute a system that matches action execution and observation in humans (see the *mirror neuron system* in Rizzolatti and Craighero 2004).

Although executing human body actions tends to be more effective than solely observing these actions and motions (e.g., Jang et al. 2017; Kontra et al. 2015; Stieff et al. 2016; Stull et al. 2018c), both executing and observing human motion trigger the mirror neuron system and are productive to cognitive processes. The following research perspectives describe the phenomena where execution or observation of human body actions can be effective for science learning and visuospatial processing.

7.2.1 Survival Cognition

Equipped with the mirror neuron system and similar imitation mechanisms, humans have evolved to learn human body actions and movements relatively easily. These actions are examples of primary biological knowledge, largely automatic and more efficient than secondary biological knowledge (see Castro-Alonso et al. this volume-b, Chap. 5; see also Castro-Alonso et al. 2019). This has links, respectively, to System 1 and System 2 of dual process theories of psychology (see Barrouillet 2011). Basically, primary biological knowledge has been evolved by our *Homo sapiens* species over thousands of generations. As a result, currently, modern humans can deal relatively easily with primary biological tasks, such as human movement tasks, because they are part of the System 1 that has helped us to survive in this world (Geary 2002).

In consequence, human body actions, including manipulations and gestures, have been evolved for survival and are relatively easy to learn (Paas and Sweller 2012; see also Sweller et al. 2019). Moreover, any other task aligned with a survival scenario will be more efficient cognitively and thus will tend to be easier. For example, Nairne et al. (2009) measured word recall in adults, comparing survival versus non-survival conditions. Survival conditions involved relating the words to hunting or gathering food *for the subsistence of the tribe*, whereas the non-survival groups related the words to hunting or gathering *for a contest*. The groups aiding survival of the species outperformed those just competing, even though all were involved in hunting and gathering. Looking to extend these findings to visualizations, Otgaar et al. (2010, Experiment 1) investigated 75 undergraduates (76% females) memorizing 30 static pictures shown on the computer. Participants were randomly allocated to three conditions. In the *survival* condition, students rated how relevant the different pictures were in helping to find food and protect from predators. In the *moving* condition, participants had to rate how important the pictures were if planning to move to a new home. In the *pleasantness* group, students rated the appeal of each picture. As predicted, analyses revealed that retention was higher in the survival condition, compared to the other two groups which were similar to each other.

An example of visuospatial tasks is provided by Nairne et al. (2012), who reported two experiments involving the visual working memory task known as Object Location Memory. In the experiments, the tasks showed line drawings and compared scenarios of survival versus no survival. In Experiment 1, 52 undergraduates (50% females) were shown 8 drawings of food items in different places onscreen. A group of students was given the instruction that the food collection was essential for survival, while the other group received the instruction that collecting was important to win a contest. In Experiment 2, 72 undergraduates (50% females) were shown 8 drawings of animals. A group was instructed that the animals had to be hunted for survival, while the other group was told that it was to win a contest. Both experiments measured accuracy in memorizing the positions of the elements from memory. Both studies revealed that location memory was higher in the survival contexts, compared to the non-survival conditions.

A key aspect of our species' survival has been our capacity to reproduce, which entails competing and succeeding for sexual mates (e.g., Geary 2008). In modern societies, these mechanisms involve understanding the behavior of other human beings and communicating between humans, as described next.

7.2.2 Social Cognition

Social cognition belongs to the communicative aspects of survival cognition and is generally more related to observing than to executing body actions. From the four social principles to facilitate multimedia learning described by Mayer (2014), we apply in this section the *embodiment principle* and the *voice principle*. The embodiment principle predicts that on-screen instructors would be more effective by using non-verbal communication cues, such as gesturing, facial expressions, and looking directly to the camera. In multimedia science modules, this principle has shown positive effects with human instructors (e.g., Pi et al. 2019; Stull et al. 2018a; van Wermeskerken et al. 2018) and cartoon pedagogical agents (e.g., Mayer and DaPra 2012; see Wouters et al. 2008). The voice principle predicts that narrations would be more effective if recorded in human voice rather than machine voice. Extending the voice principle, there are usually more substantial instructional effects on students that learn from humans rather than from machines or artificial agents.

Concerning the embodiment principle, Stull et al. (2018a) reported two experiments totaling 107 undergraduates (70% females) who studied organic chemistry videos in one of two formats. In one condition, the male instructor wrote the chemistry contents on a conventional whiteboard. Thus, the social cues from the instructor (e.g., facial expressions, eye contact, and gaze) were not observable, as he was writing on the board while giving his back to the students. In the other condition, the instructor wrote on a transparent board, so he faced the students through a transparent window in which he wrote the contents. Results on immediate learning tests showed that the transparent condition performed better.

Similarly, Wang et al. (2019) investigated 58 educational technology undergraduates studying multimedia slides about using graphics editing software. The participants were randomly assigned to two conditions: (a) the *gaze* group watched the instructor sometimes looking to the relevant parts of the multimedia, whereas (b) the *no-gaze* condition observed that the instructor always looked to the camera. Results showed that participants in the gaze condition allocated more visual attention to the relevant parts of the multimedia and presented higher learning scores, compared to the participants in the no-gaze group.

Regarding the voice principle, it can be extended to predict that most learning scenarios where the instructor looks more human and less robotic would be more effective (e.g., Press et al. 2005). This is caused by our evolved human cognitive system, that has been shaped for generations to foster human–human communication and not human–machine relationships (cf. Geary 2002, 2008). Similarly, learning human hand tasks, including manipulations and gestures, tends to be more effective from videos and animations that show natural movements than from static images without these evolved motions (e.g., Castro-Alonso et al. 2015a; see also Castro-Alonso et al. 2019).

This extension of the voice principle also applies for visuospatial processing. In an experiment with 120 adults (50% females), mostly students, P. Jansen and Lehmann (2013) reported the common better performance of males over females on mental rotations with 3D figures (see Castro-Alonso and Jansen this volume, Chap. 4). Also, when comparing abstract cube figures to human figures, P. Jansen and Lehmann (2013) observed that the rotations with human depictions presented higher scores than with abstract shapes.

In a follow-up experiment with another 120 adult participants (50% females), Voyer and Jansen (2016) measured differences in mental rotation performance among three groups completing the rotations with different 3D figures. The *non-embodied* group completed a mental rotation test with abstract 3D cubic shapes. The *partially embodied* condition attempted the test with cubic shapes that included an attached human head. The *fully embodied* group performed the rotations of images of 3D human bodies. Results of accuracy and reaction time showed the predicted direction of effects: The group with 3D human bodies outperformed that with abstract shapes and heads, which in turn, outperformed the group with abstract shapes (see also Krüger et al. 2014).

Nevertheless, sometimes social cues can also produce adverse learning effects. As predicted by cognitive load theory, presenting many social cues visually could be detrimental to learning, as simultaneously watching the learning contents plus these visual cues could overload the visuospatial processing capacity of the students (see also Castro-Alonso et al. this volume-b, Chap. 5). For example, after the encouraging findings by Stull et al. (2018a) for transparent boards aiding chemistry learning, a follow-up experiment failed to replicate these positive effects. In this later study with 64 undergraduates (69% females), Stull et al. (2018b) did not find learning differences between transparent and conventional whiteboards. Moreover, an eye tracking analysis showed that the social cues of the instructor tended to be distracting in the transparent condition, where students focused less on the learning contents, compared to the conventional groups (see also van Wermeskerken et al. 2018).

7.2.3 Signaling

Teachers and instructors can use their body to signal important information. As shown in health sciences (e.g., A. J. Hale et al. 2017) and natural sciences (e.g., Pi et al. 2019), these signaling actions indicate the students when or where the most important learning pieces can be found. The effectiveness of signaling has been supported by evidence from diverse educational areas, including science disciplines (see Castro-Alonso et al. this volume-b, Chap. 5; see also van Gog 2014). Moreover, when the human body and its limbs (e.g., arms, hands, and fingers) are the signaling devices, social cognition effects can be triggered in addition to signaling.

Much of the evidence on gestures can be related to the two research perspectives of social cognition and signaling. For example, Ouwehand et al. (2016) investigated if the gesture of finger pointing was helpful to memorize the position of pictures shown on the four quadrants of the screen. In Experiment 1, the 79 adult participants (66% females) were assessed in both pointing versus naming (verbalizing) the quadrants (e.g., "top left") when the pictures were presented for the first time (study time). In Experiment 2, the 60 adults (63% females) were assessed in both pointing versus solely observing the quadrants at study time. Results showed that, when the pictures were shown again (test time), pointing before was more effective than either naming before (Experiment 1) or observing before (Experiment 2).

Also, in a series of four experiments totaling 484 university students (71% females), Fiorella and Mayer (2016a) investigated the influence of hands drawing illustrations in videos about a physics topic (the Doppler effect). When groups of participants studying illustrations already drawn (hands not shown) were compared to groups studying the instructors' hands drawing the illustrations (hands or body shown), supporting evidence for showing the hands was found.

In addition, signaling with human limbs tend to be more effective than signaling with non-human limbs, which is also related to the mechanisms of social cognition (voice principle) described above. For example, in an experiment with 84 undergraduates (23% females) studying a video of a photography task explained by a human instructor, Pi et al. (2017) randomly assigned students to either *human signaling*, *non-human signaling*, or *non-signaling* conditions. The human signaling was made by the instructor using her hands to point to the relevant parts in the video, and the non-human signaling involved adding arrows to the relevant parts. Results revealed that human signaling was more effective than both non-human signaling and non-signaling, which did not differ between them. In an experiment with 75 psychology undergraduates (79% females) studying the formation of lightning through an animation, de Koning and Tabbers (2013) compared a group watching a picture of a hand signaling the learning elements versus a group who observed an arrow signaling. Results showed that the hand signal was more effective than the arrow signal, in all learning measures, including written retention, oral retention, and transfer.

Nevertheless, as predicted by cognitive load theory, many signals can be redundant and thus counterproductive to learning. For example, A. J. Hale et al. (2017) advised that medical teachers should not convey too much body language in their lectures, as it could be distracting. Also, Castro-Alonso et al. (2018) conducted an experiment with 104 university students (50% females) memorizing the placement of colored symbols on the screen. Results showed that including static photos of human hands signaling the symbols was counterproductive. Moreover, as shown in the experiments by Castro-Alonso et al. (2014), the negative signaling effects of the static hands were larger when the task involved more visuospatial processing, so less capacity was left to deal with the signals and the visual elements.

7.3 Embodied Cognition in Manipulations and Gestures

A conclusion at this point is that diverse research perspectives support that executing or observing human actions can be productive for learning science topics and processing visuospatial information. We now focus on the two human hand actions most investigated in science education, namely manipulations and gestures.

The research perspectives from the previous sections can describe different examples of beneficial cognitive uses of executing or observing manipulations and gestures. For example, offloaded cognition can explain the beneficial effects of using manipulative tokens for calculations, or how the gesture of tracing with the finger can aid in understanding a machine system. Similarly, the generative learning perspective can be used to explain the positive effect of manipulating anatomical models to obtain a personal angle for study and observation. Likewise, the physical activity rationale would explain the positive effects of making gestures to process more rapidly mental rotations.

Also, survival cognition would explain why it is relatively easy to learn and imitate a human manipulating a chemistry model. Similarly, social cognition predicts that learning biology topics can be boosted if the learner executes or observes the instructor making gestures. Last, the signaling research perspective can explain why it is beneficial to watch the hands drawing a science illustration or pointing to it. In short, different research perspectives can be used to explain why executing or observing manipulations and gestures would influence science learning and visuospatial processing.

In addition to both hand actions influencing sciences education and visuospatial processing, manipulations and gestures share other similarities. Chu and Kita (2008) positioned these actions on a continuum, in which manipulations were more concrete and gestures tended to be less concrete. In four experiments with adults performing mental rotations, the authors provided evidence that training on these visuospatial tasks occurred in three incremental stages. In the initial stage, mental rotations are dependent on manipulations and also on gestures that connect the hand to the rotated shapes. This was regarded as a basic stage, restricted by both the physical constraints of the manipulative shapes, and by the anatomical limitations of the hand. In the intermediate stage, mental rotations only depend on gestures (different to those on the previous stage, such as gestures that simulate the movements of the shapes), so here only the anatomical limitations of the hand are present. In the advanced stage of mental rotation performance, there is independence from both manipulations and gestures, so there are no physical limitations of the shapes or the hands, and the visuospatial processing becomes internalized. In short, manipulations need an object and are concrete, gestures need the hands and are less concrete, and the least concrete action, which is independent of objects and hands, is internal mental processing.

Castro-Alonso et al. (2015b) described a similar relationship between manipulations and gestures. They argued that manipulations are dependent on manipulative objects, whereas gestures are dependent on hands (see Fig. 7.1). Conversely, manipu-

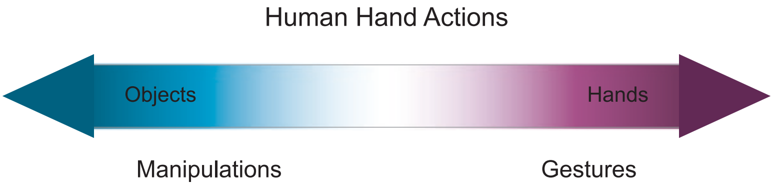


Fig. 7.1 Manipulations and gestures are human hand actions that differ in their dependence to objects and hands, respectively

Table 7.2 Examples of research on manipulations

Research	Result	References
Physical vs. virtual	Favor virtual	Barrett et al. (2015) and Stull et al. (2013)
	Favor any	Stull and Hegarty (2016)
Executing vs. observing	Favor executing	Harman et al. (1999), Jang et al. (2017), Meijer and van den Broek (2010) and Stull et al. (2018c)
Manual vs. mental	Favor manual	Adams et al. (2014)

lations can be independent of hands (e.g., Wong et al. 2009), whereas gestures can be independent of objects (e.g., Ping and Goldin-Meadow 2010). Thus, manipulations and gestures differ in their dependence to manipulatives and hands, respectively.

7.4 Manipulations

Manipulating objects and observing instructors or peers using these objects, has shown positive instructional effects on health and natural sciences. However, not all these objects, also known as *manipulatives* or *models*, are equally effective instructional assets. For example, Brown et al. (2009) suggested that simpler manipulatives would be more effective than more complex objects containing distracting features. This can also be predicted by cognitive load theory and the redundancy effect (see Castro-Alonso et al. this volume-b, Chap. 5), which discourages adding distracting and redundant information to the learning materials. Moreover, this extra information in the manipulatives can be particularly challenging for students with lower visuospatial capacity.

In this section, we describe the relationships between manipulations, science education, and visuospatial processing. In these research areas, some results have been consistently replicated, as shown in Table 7.2. For example, comparisons between physical and virtual manipulations tend to favor virtual formats. Similarly, when investigating executing versus observing manipulations, more supporting evidence is found for executing the hand tasks. Last, there are some indications where manual training seems to be more effective than only mental training, as research on rotational tasks has shown.

7.4.1 Manipulations and Science Education

Regarding health sciences, Yammine and Violato (2016) conducted a meta-analysis investigating the effectiveness of physical models versus other materials (e.g., 2D digital images, cadavers, and 3D textbooks) to learn anatomy. Although the meta-analysis was small (16 comparisons and a total of 498 students), it showed an overall medium to large mean effect size of $d = 0.73$, favoring using physical models over the other instructional materials. These positive effects of manipulations on anatomy learning do not need complicated or expensive manipulatives. For example, Chan (2015) described useful low-cost physical models made of simple materials (e.g., apron, T-shirt, hair bands, and pieces of colored paper).

In biology, there are also examples of positive outcomes for manipulations with physical objects. For biomolecular models, Roberts et al. (2005) reported that, in an undergraduate biochemistry course, physical manipulatives of proteins were effective instructional assets and were rated by the students as the most preferred tools. In a study with 32 biology or chemical engineering undergraduates (72% females), Höst et al. (2013) compared the instructional effectiveness of an image or a physical manipulative to learn about molecular self-assembly. Results of the open-ended questions showed that the manipulative was a more effective tool to understand this problematic biomolecular topic. Forbes-Lorman et al. (2016) investigated biology and biochemistry university students learning structure–function relationships in proteins. Using physical models of the proteins was beneficial for women but was not influential for men, arguably because men tend to have higher visuospatial processing (see Castro-Alonso and Jansen this volume, Chap. 4) and need to a lesser extent the offloading scaffolds provided by the manipulative models.

In addition to physical manipulations, current research has also employed computer or virtual formats (e.g., Cui et al. 2017; Skulmowski et al. 2016; Stull et al. 2009). To investigate which format was more effective in organic chemistry instruction, Stull et al. (2013, Experiment 1) recruited 29 university students (55% females). The participants were randomly assigned to either execute virtual and then physical manipulation of models, or physical and then virtual manipulations. Results showed that, independent of the format order, when students employed the virtual models, they needed less time to reach accuracy, compared to the physical manipulations. Similar findings were reported by Barrett et al. (2015) in a follow-up study with 41 psychology undergraduates (56% females). This larger efficiency of the virtual models can be explained by cognitive load theory. Virtual manipulations, having *constrained interactivity*, only permitted the motions relevant for the learning topic, whereas physical manipulations allowed more hand motions, including those not relevant for the task. A similar advantage of simulations over real-life laboratory activities is briefly discussed in Castro-Alonso and Fiorella (this volume, Chap. 6). In short, physical manipulations may include extraneous cognitive load that is not essential for learning.

As there is a distinction between physical and virtual manipulations, there can also be a difference between executing versus observing the manipulations. In two experiments, Stull et al. (2018c) investigated university students learning to interpret 2D representations of 3D organic chemistry molecules. Experiment 1 studied 61 students

(66% females) in a controlled laboratory setting, whereas Experiment 2 involved 81 students (56% females) attending a lecture in an auditorium. In both experiments, participants in the groups that manipulated the chemistry models presented higher tests scores than students who only observed the instructor's demonstrations with the models. Similarly, in four experiments with a total sample surpassing 170 adults, Kontra et al. (2015) studied executing versus observing manipulations to learn the physics concept of angular momentum. The manipulation involved holding a set of spinning bicycle wheels by the axle and tilting the axle. The four experiments showed that doing was more effective than observing the manipulations.

7.4.2 *Manipulations and Visuospatial Processing*

Arguably, the first notion of a connection between manipulations and visuospatial processing was the study of mental rotation by Shepard and Metzler (1971), in which there was a linear increase in response time as the angles between pairs of test figures were larger. In other words, to process the mental rotations between the pairs, it appeared that participants were mentally doing something equivalent to physical rotations. In a follow-up study with mental folding, Shepard and Feng (1972) observed a similar outcome, in which the more folds involved, the more time taken to answer. In other words, mental folding also seemed to be equivalent to physically folding and manipulating the pieces of paper.

The effects were replicated in later studies. For example, Wohlschläger and Wohlschläger (1998, Experiment 1) investigated 66 right-handed psychology students randomly assigned to either a mental task or a comparable manual rotation task. In both cases, the same 3D abstract shapes had to be rotated, but in the manual format this was performed twisting a knob with the right-hand. For both the mental and the manual tasks, results showed that the time taken to rotate the shapes was almost identically affected by the angular difference between the shapes. Thus, mental and manual rotations had analogous functions of response time.

In Wohlschläger and Wohlschläger (1998, Experiment 2), interference between the manual and the mental tasks were investigated on 48 right-handed psychology participants. As predicted due to common processing, results revealed that manually rotating the knob in the opposite direction of the mental rotations inhibited performance, whereas manually and mentally rotating in the same direction facilitated the response. Wexler et al. (1998) tested if this interference could also be obtained with 2D shapes. The study investigated 12 adults (50% females) executing on-screen mental rotations with simple 2D figures while performing unseen manual rotations with a joystick. When the direction of rotation for the mental and the manual tasks coincided, the mental rotations were faster and more accurate than when both tasks were incompatible. An example of these effects is shown in Fig. 7.2.

Later, Adams et al. (2014) replicated the interference effects and also investigated different rotational training regimes. In Experiment 1, regarding a mental rotation task, 68 university students (64% females) were randomly assigned to train

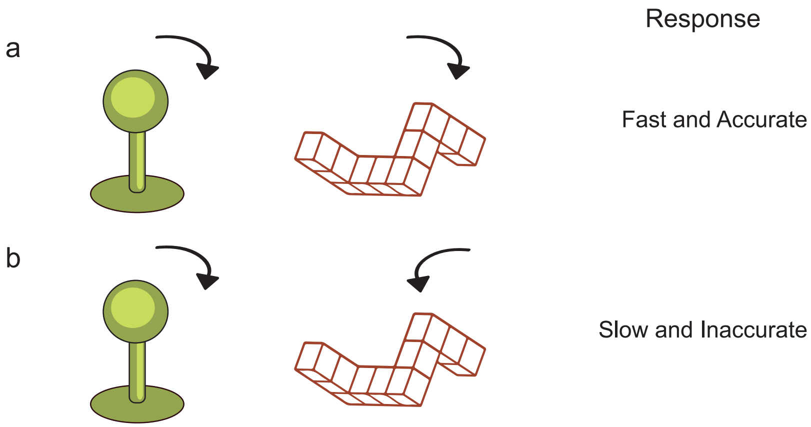


Fig. 7.2 Effects when manual rotations (knob) and mental rotations (3D shape) are (**a**) in the same direction, or (**b**) in opposite directions

in either manual rotation, mental rotation, or a verbal task (control condition). Manual rotation involved manually aligning the rotation of two abstract 3D blocks on-screen. Mental rotation, as in typical instruments, involved answering if the two abstract 3D blocks on-screen were the same but rotated shapes, or both mirrored and rotated depictions. Results on a mental rotation task showed that both manual and mental rotation training were more effective than the control condition. Experiment 2 investigated a manual rotation task performed by 65 university participants. Results revealed that manual training, but not mental training, was more effective than the control group for the manual task. In conclusion, both experiments showed that manual rotation training was effective for both manual and mental rotation tasks, but mental rotation training was only useful for the mental rotation task.

As in science education, visuospatial processing tasks have also investigated the effects of executing versus observing the manipulations. For example, Harman et al. (1999) studied 22 undergraduates (59% females) memorizing novel 3D virtual objects. In a yoked-control design, students rotating the objects on the screen were compared to students observing these manipulations by other participants. Results showed that the group doing the manipulative rotations recognized the objects faster than those observing the manipulations. Meijer and van den Broek (2010) conducted a replication experiment controlling the level of visuospatial processing of the participants. In the study, 36 university students (72% females) were assessed in their 3D mental rotation ability with the Mental Rotations Test. All participants studied novel 3D on-screen objects by: (a) rotating the objects with the computer mouse, and (b) observing the computer doing the rotations. Results revealed that the low mental rotation students presented higher performance when they could rotate the objects. In contrast, middle and high mental rotation students performed similarly when rotating or only observing the objects. In other words, their high visuospatial capacity allowed them to manage the task effectively, without the need of executing the manipulations.

The last example of doing versus observing is provided with a task resembling Object Location Memory. In the study, Trewartha et al. (2015, Experiment 1) investigated 12 adult participants assigned to the executing or watching condition. In the executing group, participants discovered the spatial locations of virtual objects by moving a robotic arm to uncover the objects. In the watching condition, the robotic arm moved by itself. Consistent with the literature for executing over observing hand actions, the results showed that the group doing manipulations to uncover the hidden objects was more accurate than the condition solely observing these actions.

7.4.3 Manipulations, Science Education, and Visuospatial Processing

Accumulating evidence is supporting that high visuospatial processing individuals profit more from the positive effects of manipulations on science learning than low visuospatial processing individuals. For example, in the field of anatomy, Stull et al. (2009) reported two experiments with a total of 133 university students (63% females) performing rotational manipulations of a 3D computer model of a bone (the human sixth cervical vertebra). In each experiment, a median split of the scores on the Mental Rotations Test defined low and high spatial ability students. Consistent results in both experiments showed that high mental rotation students outperformed their lower counterparts in being more accurate and direct to execute the manual rotations of the virtual model.

Regarding biology, Huk (2006) examined 106 undergraduate and high school students (67% females) learning the structure of plant and animal cells through interactive multimedia. To measure the mental rotation ability of the students, a 3D instrument was used, namely, the Tube Figures Test. Also, half of the sample could manipulate 3D virtual models of the cells, to investigate their effects on understanding the cellular structures. Results revealed that only high mental rotation students benefited from manipulating the 3D models. In other words, spatial processing was needed to cope with the mental demands of using 3D models. Similarly, for chemistry tasks, in two experiments with a total of 267 university students (51% females), Barrett and Hegarty (2016) showed that mental rotation and spatial ability were fundamental to manipulate virtual organic chemistry molecules.

Research about visuospatial processing and science education has also compared virtual and physical manipulations. For example, Stull and Hegarty (2016) conducted two experiments with undergraduate organic chemistry students using models to solve problems about translations of chemical representations. In both experiments, the effectiveness of different virtual and physical models of chemical molecules was compared. Also, in both studies mental rotation was measured with an online version of the Mental Rotations Test. In Experiment 1, which investigated 105 students (54% females), the virtual models presented low fidelity (low action-congruence), so their manipulations were performed using a computer mouse and keyboard.

In contrast, in Experiment 2, with 104 participants (65% females), the virtual model presented high fidelity (high action-congruence), so their manipulations were performed using a virtual reality system with a hand-held device and stereo glasses. The two experiments showed that the groups using models outperformed the control groups in translation accuracy between representations. The type of model did not affect these results, as both the virtual models (low and high fidelity) and the physical models were equally effective. It was also reported that mental rotation was a significant predictor of achievement in these molecular translations, but not as influential as the employment of manipulatives. In conclusion, these results are not as supportive of the computer manipulations over the physical formats as those described in Sect. 7.4.1.

Last, research combining the effects of manipulations, science instruction, and visuospatial processing has also investigated executing versus observing manipulations. For instance, in the realm of anatomy, Jang et al. (2017) examined 76 medical university participants (42% females) studying a 3D virtual model of the inner ear in a stereoscopic 3-D environment. Visuospatial processing was measured with the Mental Rotations Test. Results showed that participants that manipulated the model outperformed those that watched the model being manipulated. In addition, from the students that watched the manipulations, higher mental rotations predicted higher anatomy learning outcomes. This relationship between mental rotation and anatomy learning was absent in those that manipulated the model. Arguably, manipulating the model resulted in less investment of visuospatial processing (mental rotation), whereas only watching relied on this processing to learn the anatomical structures. Consequently, either manipulation or high mental rotation ability were key assets to understand the anatomy task.

7.5 Gestures

Gestures are hand motions that convey effective nonverbal communication when executed and observed (see Hall et al. 2019). Although they have been habitually connected to the social cognition and signaling research perspectives, we have shown that gestures are linked to all the embodied perspectives discussed in this chapter. As nonverbal assets, they convey additional information to that of speech, so they are useful tools for learners and instructors. For example, in a meta-analysis of 38 experiments (63 effect sizes; $N = 2{,}396$), Hostetter (2011) compared the effects of *speech-only* vs. *speech plus gesture* conditions on memory or learning. The effect of adding human gestures to speech showed an overall medium size of $d = 0.61$. The effect presented a comparable size if the performer of the gestures was following a script or was making the gestures spontaneously. The most useful gestures were those used to

Table 7.3 Examples of research on gestures

Research	Result	References
Executing vs. observing	Favor executing	Stieff et al. (2016)
Outside the task	Hinders	S. Hale et al. (1996) and Lawrence et al. (2001)
Inside the task	Enhances	Chum et al. (2007) and Göksun et al. (2013)

convey a spatial or motor idea, which indicated a relationship between gestures and visuospatial processing.

In addition to the findings on human gesturing, there are also positive effects of gestures produced by cartoon or animated agents. For example, Davis (2018) conducted a meta-analysis of 20 experiments ($N = 3{,}841$) and $k = 41$ pairwise comparisons that contrasted animated agents making gestures versus agents' static images or voices. The results revealed that the agents that included gestures produced better retention ($g = 0.28$, $k = 7$) and near transfer ($g = 0.39$, $k = 16$) learning scores than agents not gesturing. These are small effect sizes supporting the inclusion of gestures in animated pedagogical agents.

In this section, we describe the relationships between gestures, science education, and visuospatial processing. As with manipulations, research on gestures has shown some consistent trends, presented in Table 7.3. For example, comparisons between executing and observing gestures have found more supporting evidence for executing these hand motions. Also, there are consistent results that show that gesturing outside the visual stimuli is counterproductive, whereas gesturing toward the stimuli is productive.

7.5.1 Gestures and Science Education

In the meta-analysis just described, Davis (2018) investigated the moderating effects of topics on gesturing by animated agents. Results showed that the near transfer scores tended to be larger for science topics ($g = 0.47$), compared to maths ($g = 0.32$) and humanities ($g = 0.08$), although the difference was not significant. This result highlights the importance of gestures for science topics, in this case, made by cartoon agents (see also Li et al. 2019).

However, most of the research on gestures for science education deals with humans as executers and observers of gestures. For examples where the students executed the gestures, the action of *tracing* can be considered. Tracing is a gesture that comprises finger motion following a path or movement (Hegarty et al. 2005) typically against paper or other surfaces (Ginns et al. 2016).

In an experiment with 10 undergraduates studying static mechanical diagrams, Hegarty et al. (2005, Experiment 1) observed that producing tracing gestures facilitated mentally animating the diagrams and understanding their mechanisms.

Tang et al. (2019) randomly assigned 46 school students to either study by reading lesson materials on the water cycle, or tracing out key water cycle processes (e.g., evaporation) while studying. Students who traced while studying subsequently outperformed the control group on both retention and transfer tests.

In addition to these science examples, Ginns et al. (2016) provided two experiments of maths topics. In Experiment 1, involving the spatial topic of triangle geometry, the participants were 52 school boys. In Experiment 2, regarding the non-spatial topic of order of operations, the participants were 54 school students (59% females). In both experiments, the students were randomly assigned to the experimental condition of executing tracing versus control conditions without tracing. The results on the transfer tests for both experiments showed that the tracing groups outperformed the non-tracing conditions.

An example besides executing tracing is the study by Pi et al. (2019), which concerns observation of gestures for biology education. In the experiment, 120 university students from diverse disciplines (78% females) studied a video lecture about reproduction and cloning. The video showed a teacher looking into the camera while explaining the content slides at her side. The participants were randomly assigned to one of four learning groups: (a) *control* (no gazing and no gesturing), (b) *gazing only*, (c) *gesturing only*, and (d) *gazing and gesturing*. In both gazing conditions, the teacher in the video looked to the relevant areas on the slide. In both gesturing conditions, the teacher used fingers and hands to point to the relevant areas. Results showed that the conditions with gesturing significantly outperformed the control group, for both retention and transfer tests.

Is it better to execute or to observe gestures for science learning? Aligned to the previous sections on manipulations, the evidence on gestures also show the tendency that executing is better than solely observing the hand actions. For example, Stieff et al. (2016) reported two experiments with organic chemistry undergraduates attempting translations between organic chemistry molecular representations. In Study 1 ($N = 70$), the participants were randomly allocated to one of three conditions: (a) control text-only group, (b) observed gestures, and (c) observed and executed gestures. Results showed that the most effective group for molecular equivalencies was that watching the experimenter making the gestures and then imitating the hand movements. Also, solely watching the gestures (observed gestures condition) was not more effective than not watching them (control condition). Study 2 ($N = 104$) replicated these positive results for observing and doing.

7.5.2 Gestures and Visuospatial Processing

The relationship between gestures and visuospatial processing has been supported by experiments showing deleterious effects of gesturing toward the outside of the visuospatial task and beneficial effects of gesturing toward the stimuli. Examples of the first line of evidence are provided in the interference experiments by S. Hale et al. (1996), who investigated undergraduates performing single and dual tasks of working memory. One of the tasks was the Location Span Task, which involved memorizing sequences of a mark randomly positioned on a 4 x 4 grid. In Experiment 1A ($N = 30$), results showed that pointing with the finger aside the stimuli impaired performance on the Location Span Task. A follow-up (Experiment 3, $N = 20$) revealed that moving the eyes aside the stimuli was also detrimental, and that moving the eyes and pointing aside was more deleterious. Similarly, Lawrence et al. (2001) investigated 18 undergraduates executing a spatial working memory task of memorizing randomly colored positions on a square grid. Results showed that the task was impaired by moving a finger toward a peripheral flash.

Concerning evidence of positive effects of gesturing to the visuospatial task, Chum et al. (2007) reported two experiments with a total of 37 psychology undergraduates performing spatial working memory tasks in which visual sequences had to be replicated from memory, as in the Corsi Block Tapping Test. As in this test, each sequence included shapes that were placed in different positions. Each experiment involved comparisons between executing pointing gestures versus not executing these gestures. The pointing was aimed at every position of the visual elements in the sequences. Results on the scores of this visuospatial working memory test revealed that pointing was more effective than not pointing. An example of these results is given in Fig. 7.3.

Another effective gesturing example is provided by So et al. (2015), who investigated 138 undergraduates (54% females) learning difficult map routes. The visuospatial processing of the participants was calculated by combining the scores on a mental folding task (Paper Folding Test) and a spatial working memory task (Corsi Block Tapping Test). Groups of students allowed to execute gestures were compared to groups in which gesturing was not allowed. Results revealed that the most important predictor for recall about the routes was being allowed to gesture while memorizing. Visuospatial processing, although helpful, had a secondary influence.

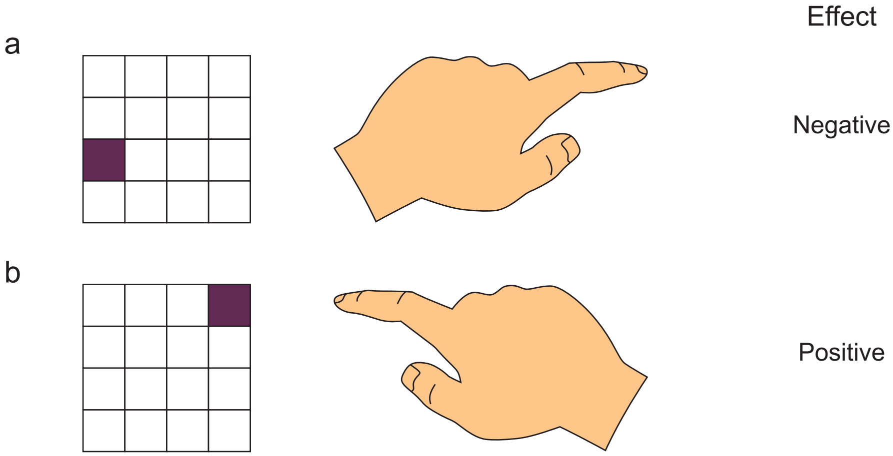


Fig. 7.3 Effects when executing a pointing gesture either (**a**) away of the visuospatial task, or (**b**) toward the visuospatial task

Last, Göksun et al. (2013) investigated 28 adults executing gestures while doing mental rotations of physical shapes. Also, low versus high mental rotators were compared, according to the scores on the Mental Rotations Test. Results showed that low mental rotators produced more gesturing while solving the rotations, compared to the high mental rotation participants. Thus, gesturing was effective to offload cognition, and this was particularly helpful for those at the limits of their visuospatial processing capacity.

7.5.3 Gestures, Science Education, and Visuospatial Processing

The difference between executing and observing hand actions can also be made here. An example of the beneficial educational effects of executing gestures is provided in the physics disciplines by Hegarty et al. (2005, Experiment 2), who recruited 45 undergraduates to perform mental animations of static mechanical diagrams. To investigate the effects of doing gestures and visuospatial processing, a group of students executing a spatial tapping interference task was compared to a control without this load on the visuospatial processor. As predicted, results showed that spatial tapping prevented executing gestures and hindered mental animation of the mechanical systems.

In a follow-up with 60 undergraduates by Hegarty et al. (2005, Experiment 3), the comparison was made between a spatial tapping group, a gesture-restricted group, and a control group (without spatial tapping and allowed to gesture). Results revealed that the gesture-restricted and the control groups outperformed the spatial tapping condition. In other words, these mental animations tasks relied more on visuospatial processing (interfered by spatial tapping) than on gesturing (interfered by gesture-restrictions). In all, these two experiments support that visuospatial processing is the primary asset for the mental animation of static mechanical diagrams, and that executing gestures may be a secondary but effective resource. This order of effects contrasts with the findings by So et al. (2015), described in the previous section, where executing gestures was more important than visuospatial processing.

Another piece of evidence showing positive effects of executing gestures is the study by Pouw et al. (2016) with 20 adults (75% females) attempting the visual puzzle known as the Tower of Hanoi. In the study, visual working memory was assessed with the Visual Patterns Test. Results showed that, while the participants were solving the puzzle, executing pointing gestures reduced their eye movements. This efficient mechanism was larger for those with lower scores in the visual working memory test. Thus, these results support that executing gestures can alleviate part of the burden in the eye movement and visuospatial processing (see similar findings in Eielts et al. 2018).

An example of beneficial effects of observing gestures is provided in the biology fields by Brucker et al. (2015), who investigated 45 university students (69% females) learning about fish movements from dynamic visualizations supplemented with gestures of these motions. In addition, visuospatial processing ability was measured with the mental folding task known as the Paper Folding Test. It was observed that, when students watched gestures that corresponded with the fish movements, low visuospatial learners were benefited, but these motions did not affect high visuospatial students. It was argued that high visuospatial students could understand the fish locomotions without the scaffolds provided by observing gestural information.

The last example is illustrative of the importance of visuospatial processing for understanding gestures, although it involves the observation of gestures about everyday activities rather than science topics. It concerns four experiments, conducted by Y. C. Wu and Coulson (2014), sampling a total of 251 university students (65% females). In the study, photos of activities in which the speech was congruent to the gesture (e.g., describing screwing while moving the hand clockwise) were compared to photos in which speech and gesture were incongruent. Spatial working memory was measured with a computer version of the Corsi Block Tapping Test. Results showed that the fastest students to integrate the speech–gesture congruent information were those with higher scores in the spatial working memory test. Moreover, this effect was reduced when the participants performed a simultaneous visuospatial task, but was not affected when doing a simultaneous verbal task. In conclusion, the experiments supported that visuospatial processing was more necessary than verbal processing for understanding gesture plus speech information. It can be predicted that, for a science topic described by the instructor with gestures and speech, students with higher visuospatial processing will understand more from observing the gestures, compared to students with lower visuospatial processing.

7.6 Discussion

Embodied cognition phenomena can be triggered when executing or observing body actions. When solely executing body actions, three non-mutually exclusive experiences can happen, namely: (a) offloaded cognition, (b) generative learning, and (c) physical activity. The action of offloading cognition to the body and the environment can produce a cognitive boost, particularly helpful for students whose visuospatial processing is being challenged by the difficulty of the visuospatial information. Regarding generative learning phenomena, in addition to allowing offloading cognition, it can add a personal touch to the executer. For example, drawing puts information onto the environment (offloaded cognition), but these depictions use personal styles (generative learning). Last, physical activity, including vigorous and calmed activity, can boost immediate cognitive performance. Also, the positive effects can be sustained in time.

In addition, there are also experiences when either executing or observing body actions, that research has termed as: (a) survival cognition, (b) social cognition, and (c) signaling. Concerning survival cognition, our human cognition has always equipped us to survive, so cognitive tasks of today are more effective if they resemble the tasks our ancestors used for subsistence. One of these tasks was to communicate with other humans, so survival and social cognition have equipped us to understand the social cues of others, which is more effective if these others are humans and not machines or robots. Last, some of these social cues involve signaling relevant information. In these cases, signaling and social cueing co-occur.

The human motions mostly researched about these different embodied phenomena concern object manipulation and gestures, which have been useful assets in diverse fields of health and natural sciences, including anatomy, biology, chemistry, and physics. Also, manipulations and gestures are effective tools for visuospatial processing.

Regarding the type of manipulation, both physical and virtual manipulations have shown effectiveness, but in the studies where these formats have been compared, usually the virtual format is favored. Another common comparison in manipulation research is between executing and observing others executing the actions. In these cases, the typical trend is that executing is more effective than only observing.

Concerning gestures research, the findings also show that doing the hand actions tends to be better than solely observing them. However, observing the gestures of human teachers and instructors, as well as animated pedagogical agents, is also effective to learn health and natural science topics. In these disciplines, encouraging results are showing how gesturing can be helpful for students with lower visuospatial processing.

7.6.1 Instructional Implications for Health and Natural Sciences

Concerning executing body actions, many different physical activities, at different degrees of energy demands, can have positive effects on cognitive processes. An instructional implication is that teachers could promote low-intensity physical exercising (e.g., walking, manipulations, and gestures) as effective activities for science education.

A second instructional implication considers the survival cognition perspective. As such, learning activities could be framed in survival scenarios, such as hunting wild animals or collecting food to avoid starvation. In principle, any learning task with these added survival cues could be more effective than a version without this subsistence component.

Following the extension to the voice principle of social cognition, a third implication is that learning tasks should prioritize human–human interactions, and similar socially evolved mechanisms. For example, for tasks of manipulations and gestures, videos or live action may be preferable to static images, and humans doing the hand tasks may be preferable to robots or virtual agents.

An implication for manipulations is based on the aim of reducing visuospatial information. This fourth implication is to foster simple manipulatives, as they tend to produce meaningful learning. Similarly, virtual manipulations may be simpler and preferable to physical manipulations.

The fifth and last implication concerns gestures. Allowing students to execute gestures while learning science topics should be promoted, particularly in those individuals with lower visuospatial abilities.

7.6.2 Future Research Directions

Regarding the execution of body actions, future research could investigate which movement or action is best to train visuospatial processing. Similarly, further investigations could search for the most effective intensity and duration of training specific physical activity to boost cognitive functions.

Concerning the observation of hand actions, future research may reveal the best conditions to provide adequate social cognition and signaling, without also implying additional visuospatial information that could be difficult to handle, particularly for students with lower working memory capacity.

Future research needs to investigate further the relationship between science education and visuospatial processing (see Castro-Alonso and Uttal this volume, Chap. 3). For example, to establish better links between visuospatial processing assisting science learning, and science education helping visuospatial processing (see also Castro-Alonso and Uttal 2019), the addition of manipulative or gesturing actions can be considered. Similarly, interactive multimedia (see Castro-Alonso and Fiorella this volume, Chap. 6) and modern technological devices will provide new instructional possibilities for science education and human hand actions.

As sex and gender are influential to visuospatial processing and learning (see Castro-Alonso and Jansen this volume, Chap. 4; see also Castro-Alonso et al. 2019), their effects on embodied cognition are worth investigating. For example, research has shown that females tend to use more information than males from observing gestures and nonverbal communication (see Hall et al. 2019), so this effect could be investigated for science learning or visuospatial tasks.

7.6.3 Conclusion

Different research perspectives have investigated the phenomena of embodied cognition, which can be activated when executing or observing human body movements. Two of the most investigated embodied phenomena are manipulations and gestures, which can be executed and observed for effective science education and visuospatially processing. Regarding manipulations, it seems that virtual manipulatives are more effective than physical models. Regarding gestures, they are valuable assets, sometimes combined with visuospatial processing, to learn health and natural science topics. For both manipulations and gestures, a common finding is that executing these hand actions is more instructionally effective than solely observing them.

Acknowledgments Support from PIA–CONICYT Basal Funds for Centers of Excellence Project FB0003 is gratefully acknowledged. The first author is thankful to Monserratt Ibáñez for her assistance.

References

Adams, D. M., Stull, A. T., & Hegarty, M. (2014). Effects of mental and manual rotation training on mental and manual rotation performance. *Spatial Cognition and Computation, 14*(3), 169–198. https://doi.org/10.1080/13875868.2014.913050.

Barrett, T. J., & Hegarty, M. (2016). Effects of interface and spatial ability on manipulation of virtual models in a STEM domain. *Computers in Human Behavior, 65*, 220–231. https://doi.org/10.1016/j.chb.2016.06.026.

Barrett, T. J., Stull, A. T., Hsu, T. M., & Hegarty, M. (2015). Constrained interactivity for relating multiple representations in science: When virtual is better than real. *Computers & Education, 81*, 69–81. https://doi.org/10.1016/j.compedu.2014.09.009.

Barrouillet, P. (2011). Dual-process theories and cognitive development: Advances and challenges. *Developmental Review, 31*(2–3), 79–85. https://doi.org/10.1016/j.dr.2011.07.002.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639.

Brown, M. C., McNeil, N. M., & Glenberg, A. M. (2009). Using concreteness in education: Real problems, potential solutions. *Child Development Perspectives, 3*(3), 160–164. https://doi.org/10.1111/j.1750-8606.2009.00098.x.

Brucker, B., Ehlis, A.-C., Häußinger, F. B., Fallgatter, A. J., & Gerjets, P. (2015). Watching corresponding gestures facilitates learning with animations by activating human mirror-neurons: An fNIRS study. *Learning and Instruction, 36*, 27–37. https://doi.org/10.1016/j.learninstruc.2014.11.003.

Castro-Alonso, J. C., & Atit, K. (this volume). Different abilities controlled by visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 23–51). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_2.

Castro-Alonso, J. C., & Fiorella, L. (this volume). Interactive science multimedia and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 145–173). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_6.

Castro-Alonso, J. C., & Jansen, P. (this volume). Sex differences in visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 81–110). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_4.

Castro-Alonso, J. C., & Uttal, D. H. (2019). Spatial ability for university biology education. In S. Nazir, A.-M. Teperi, & A. Polak-Sopińska (Eds.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2018 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 283–291). Cham: Springer. https://doi.org/10.1007/978-3-319-93882-0_28.

Castro-Alonso, J. C., & Uttal, D. H. (this volume). Science education and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 53–79). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_3.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2014). Learning from observing hands in static and animated versions of non-manipulative tasks. *Learning and Instruction, 34*, 11–21. https://doi.org/10.1016/j.learninstruc.2014.07.005.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015a). Animations showing Lego manipulative tasks: Three potential moderators of effectiveness. *Computers & Education, 85*, 1–13. https://doi.org/10.1016/j.compedu.2014.12.022.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015b). The potential of embodied cognition to improve STEAM instructional dynamic visualizations. In X. Ge, D. Ifenthaler, & J. M. Spector (Eds.), *Emerging technologies for STEAM education: Full STEAM ahead* (pp. 113–136). New York: Springer. https://doi.org/10.1007/978-3-319-02573-5_7.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2018). Learning symbols from permanent and transient visual presentations: Don't overplay the hand. *Computers & Education, 116*, 1–13. https://doi.org/10.1016/j.compedu.2017.08.011.

Castro-Alonso, J. C., Wong, M., Adesope, O. O., Ayres, P., & Paas, F. (2019). Gender imbalance in instructional dynamic versus static visualizations: A meta-analysis. *Educational Psychology Review, 31*(2), 361–387. https://doi.org/10.1007/s10648-019-09469-1.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (this volume-a). VAR: A battery of computer-based instruments to measure visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 207–229). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_8.

Castro-Alonso, J. C., Ayres, P., & Sweller, J. (this volume-b). Instructional visualizations, cognitive load theory, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 111–143). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_5.

Chan, L. K. (2015). The use of low-tech models to enhance the learning of anatomy. In L. K. Chan & W. Pawlina (Eds.), *Teaching anatomy: A practical guide* (pp. 259–266). Cham: Springer. https://doi.org/10.1007/978-3-319-08930-0_29.

Chi, M. T. H., De Leeuw, N., Chiu, M.-H., & Lavancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18*(3), 439–477.

Choi, H.-H., van Merriënboer, J. J. G., & Paas, F. (2014). Effects of the physical environment on cognitive load and learning: Towards a new model of cognitive load. *Educational Psychology Review, 26*(2), 225–244. https://doi.org/10.1007/s10648-014-9262-6.

Chu, M., & Kita, S. (2008). Spontaneous gestures during mental rotation tasks: Insights into the microdevelopment of the motor strategy. *Journal of Experimental Psychology: General, 137*(4), 706–723. https://doi.org/10.1037/a0013157.

Chum, M., Bekkering, H., Dodd, M. D., & Pratt, J. (2007). Motor and visual codes interact to facilitate visuospatial memory performance. *Psychonomic Bulletin & Review, 14*(6), 1189–1193. https://doi.org/10.3758/bf03193111.

Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis, 58*(1), 7–19. https://doi.org/10.1093/analys/58.1.7.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale: Erlbaum.

Cracco, E., Bardi, L., Desmet, C., Genschow, O., Rigoni, D., De Coster, L., et al. (2018). Automatic imitation: A meta-analysis. *Psychological Bulletin, 144*(5), 453–500. https://doi.org/10.1037/bul0000143.

Cui, D., Wilson, T. D., Rockhold, R. W., Lehman, M. N., & Lynch, J. C. (2017). Evaluation of the effectiveness of 3D vascular stereoscopic models in anatomy instruction for first year medical students. *Anatomical Sciences Education, 10*(1), 34–45. https://doi.org/10.1002/ase.1626.

Davis, R. O. (2018). The impact of pedagogical agent gesturing in multimedia learning environments: A meta-analysis. *Educational Research Review, 24*, 193–209. https://doi.org/10.1016/j.edurev.2018.05.002.

de Koning, B. B., & Tabbers, H. K. (2013). Gestures in instructional animations: A helping hand to understanding non-human movements? *Applied Cognitive Psychology, 27*(5), 683–689. https://doi.org/10.1002/acp.2937.

Eielts, C., Pouw, W., Ouwehand, K., van Gog, T., Zwaan, R. A., & Paas, F. (2018). Co-thought gesturing supports more complex problem solving in subjects with lower visual working-memory capacity. *Psychological Research*. Advance online publication. https://doi.org/10.1007/s00426-018-1065-9.

Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Motor facilitation during action observation: A magnetic stimulation study. *Journal of Neurophysiology, 73*(6), 2608–2611.

Fenesi, B., Lucibello, K., Kim, J. A., & Heisz, J. J. (2018). Sweat so you don't forget: Exercise breaks during a university lecture increase on-task attention and learning. *Journal of Applied Research in Memory and Cognition, 7*(2), 261–269. https://doi.org/10.1016/j.jarmac.2018.01.012.

Fiorella, L., & Mayer, R. E. (2013). The relative benefits of learning by teaching and teaching expectancy. *Contemporary Educational Psychology, 38*(4), 281–288. https://doi.org/10.1016/j.cedpsych.2013.06.001.

Fiorella, L., & Mayer, R. E. (2016a). Effects of observing the instructor draw diagrams on learning from multimedia messages. *Journal of Educational Psychology, 108*(4), 528–546. https://doi.org/10.1037/edu0000065.

Fiorella, L., & Mayer, R. E. (2016b). Eight ways to promote generative learning. *Educational Psychology Review, 28*(4), 717–741. https://doi.org/10.1007/s10648-015-9348-9.

Fiorella, L., & Mayer, R. E. (2017). Spontaneous spatial strategy use in learning from scientific text. *Contemporary Educational Psychology, 49*, 66–79. https://doi.org/10.1016/j.cedpsych.2017.01.002.

Forbes-Lorman, R. M., Harris, M. A., Chang, W. S., Dent, E. W., Nordheim, E. V., & Franzen, M. A. (2016). Physical models have gender-specific effects on student understanding of protein structure–function relationships. *Biochemistry and Molecular Biology Education, 44*(4), 326–335. https://doi.org/10.1002/bmb.20956.

Geary, D. C. (2002). Principles of evolutionary educational psychology. *Learning and Individual Differences, 12*(4), 317–345. https://doi.org/10.1016/s1041-6080(02)00046-8.

Geary, D. C. (2008). An evolutionarily informed education science. *Educational Psychologist, 43*(4), 179–195. https://doi.org/10.1080/00461520802392133.

Ginns, P., & Kydd, A. (2019). Learning human physiology by pointing and tracing: A cognitive load approach. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (119–129). New York: Routledge. https://doi.org/10.4324/9780429283895-10.

Ginns, P., Chandler, P., & Sweller, J. (2003). When imagining information is effective. *Contemporary Educational Psychology, 28*(2), 229–251. https://doi.org/10.1016/S0361-476X(02)00016-4.

Ginns, P., Hu, F.-T., Byrne, E., & Bobis, J. (2016). Learning by tracing worked examples. *Applied Cognitive Psychology, 30*(2), 160–169. https://doi.org/10.1002/acp.3171.

Göksun, T., Goldin-Meadow, S., Newcombe, N., & Shipley, T. (2013). Individual differences in mental rotation: What does gesture tell us? *Cognitive Processing, 14*(2), 153–162. https://doi.org/10.1007/s10339-013-0549-1.

Hale, S., Myerson, J., Rhee, S. H., Weiss, C. S., & Abrams, R. A. (1996). Selective interference with the maintenance of location information in working memory. *Neuropsychology, 10*(2), 228–240. https://doi.org/10.1037/0894-4105.10.2.228.

Hale, A. J., Freed, J., Ricotta, D., Farris, G., & Smith, C. C. (2017). Twelve tips for effective body language for medical educators. *Medical Teacher, 39*(9), 914–919. https://doi.org/10.1080/0142159X.2017.1324140.

Hall, J. A., Horgan, T. G., & Murphy, N. A. (2019). Nonverbal communication. *Annual Review of Psychology, 70*, 271–294. https://doi.org/10.1146/annurev-psych-010418-103145.

Harman, K. L., Humphrey, G. K., & Goodale, M. A. (1999). Active manual control of object views facilitates visual recognition. *Current Biology, 9*(22), 1315–1318. https://doi.org/10.1016/S0960-9822(00)80053-6.

Hegarty, M., & Steinhoff, K. (1997). Individual differences in use of diagrams as external memory in mechanical reasoning. *Learning and Individual Differences, 9*(1), 19–42. https://doi.org/10.1016/S1041-6080(97)90018-2.

Hegarty, M., Mayer, S., Kriz, S., & Keehner, M. (2005). The role of gestures in mental animation. *Spatial Cognition and Computation, 5*(4), 333–356. https://doi.org/10.1207/s15427633scc0504_3.

Henkel, L. A. (2014). Point-and-shoot memories: The influence of taking photos on memory for a museum tour. *Psychological Science, 25*(2), 396–402. https://doi.org/10.1177/0956797613504438.

Hoogerheide, V., Renkl, A., Fiorella, L., Paas, F., & van Gog, T. (2019). Enhancing example-based learning: Teaching on video increases arousal and improves problem-solving performance. *Journal of Educational Psychology, 111*(1), 45–56. https://doi.org/10.1037/edu0000272.

Höst, G. E., Larsson, C., Olson, A., & Tibell, L. A. E. (2013). Student learning about biomolecular self-assembly using two different external representations. *CBE Life Sciences Education, 12*(3), 471–482. https://doi.org/10.1187/cbe.13-01-0011.

Hostetter, A. B. (2011). When do gestures communicate? A meta-analysis. *Psychological Bulletin, 137*(2), 297–315. https://doi.org/10.1037/a0022128.

Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. *Journal of Computer Assisted Learning, 22*(6), 392–404. https://doi.org/10.1111/j.1365-2729.2006.00180.x.

Jang, S., Vitale, J. M., Jyung, R. W., & Black, J. B. (2017). Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. *Computers & Education, 106*, 150–165. https://doi.org/10.1016/j.compedu.2016.12.009.

Jansen, P., & Lehmann, J. (2013). Mental rotation performance in soccer players and gymnasts in an object-based mental rotation task. *Advances in Cognitive Psychology, 9*(2), 92–98. https://doi.org/10.5709/acp-0135-8.

Jansen, P., Zayed, K., & Osmann, R. (2016). Gender differences in mental rotation in Oman and Germany. *Learning and Individual Differences, 51*, 284–290. https://doi.org/10.1016/j.lindif.2016.08.033.

Jansen, R. S., Lakens, D., & Ijsselsteijn, W. A. (2017). An integrative review of the cognitive costs and benefits of note-taking. *Educational Research Review, 22*, 223–233. https://doi.org/10.1016/j.edurev.2017.10.001.

Kiefer, M., & Trumpp, N. M. (2012). Embodiment theory and education: The foundations of cognition in perception and action. *Trends in Neuroscience and Education, 1*(1), 15–20. https://doi.org/10.1016/j.tine.2012.07.002.

Kontra, C., Lyons, D. J., Fischer, S. M., & Beilock, S. L. (2015). Physical experience enhances science learning. *Psychological Science, 26*(6), 737–749. https://doi.org/10.1177/0956797615569355.

Krüger, M., Amorim, M.-A., & Ebersbach, M. (2014). Mental rotation and the motor system: Embodiment head over heels. *Acta Psychologica, 145*, 104–110. https://doi.org/10.1016/j.actpsy.2013.11.004.

Lawrence, B. M., Myerson, J., Oonk, H. M., & Abrams, R. A. (2001). The effects of eye and limb movements on working memory. *Memory, 9*(4–6), 433–444. https://doi.org/10.1080/09658210143000047.

Li, W., Wang, F., Mayer, R. E., & Liu, H. (2019). Getting the point: Which kinds of gestures by pedagogical agents improve multimedia learning? *Journal of Educational Psychology.* Advance online publication. https://doi.org/10.1037/edu0000352.

Macken, L., & Ginns, P. (2014). Pointing and tracing gestures may enhance anatomy and physiology learning. *Medical Teacher, 36*(7), 596–601. https://doi.org/10.3109/0142159X.2014.899684.

Marsh, E. J., & Rajaram, S. (2019). The digital expansion of the mind: Implications of internet usage for memory and cognition. *Journal of Applied Research in Memory and Cognition, 8*(1), 1–14. https://doi.org/10.1016/j.jarmac.2018.11.001.

Mayer, R. E. (2014). Principles based on social cues in multimedia learning: Personalization, voice, image, and embodiment principles. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 345–368). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.017.

Mayer, R. E., & DaPra, C. S. (2012). An embodiment effect in computer-based learning with animated pedagogical agents. *Journal of Experimental Psychology: Applied, 18*(3), 239–252. https://doi.org/10.1037/a0028616.

Meijer, F., & van den Broek, E. L. (2010). Representing 3D virtual objects: Interaction between visuo-spatial ability and type of exploration. *Vision Research, 50*(6), 630–635. https://doi.org/10.1016/j.visres.2010.01.016.

Moreau, D., Clerc, J., Mansy-Dannay, A., & Guerrien, A. (2012). Enhancing spatial ability through sport practice. *Journal of Individual Differences, 33*(2), 83–88. https://doi.org/10.1027/1614-0001/a000075.

Nairne, J. S., Pandeirada, J. N. S., Gregory, K. J., & Van Arsdall, J. E. (2009). Adaptive memory: Fitness relevance and the hunter-gatherer mind. *Psychological Science, 20*(6), 740–746. https://doi.org/10.1111/j.1467-9280.2009.02356.x.

Nairne, J. S., VanArsdall, J. E., Pandeirada, J. N. S., & Blunt, J. R. (2012). Adaptive memory: Enhanced location memory after survival processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(2), 495–501. https://doi.org/10.1037/a0025728.

Oppezzo, M., & Schwartz, D. L. (2014). Give your ideas some legs: The positive effect of walking on creative thinking. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(4), 1142–1152. https://doi.org/10.1037/a0036577.

Otgaar, H., Smeets, T., & van Bergen, S. (2010). Picturing survival memories: Enhanced memory after fitness-relevant processing occurs for verbal and visual stimuli. *Memory & Cognition, 38*(1), 23–28. https://doi.org/10.3758/mc.38.1.23.

Ouwehand, K., van Gog, T., & Paas, F. (2016). Effects of pointing compared with naming and observing during encoding on item and source memory in young and older adults. *Memory, 24*(9), 1243–1255. https://doi.org/10.1080/09658211.2015.1094492.

Paas, F., & Sweller, J. (2012). An evolutionary upgrade of cognitive load theory: Using the human motor system and collaboration to support the learning of complex cognitive tasks. *Educational Psychology Review, 24*(1), 27–45. https://doi.org/10.1007/s10648-011-9179-2.

Pi, Z., Hong, J., & Yang, J. (2017). Effects of the instructor's pointing gestures on learning performance in video lectures. *British Journal of Educational Technology, 48*(4), 1020–1029. https://doi.org/10.1111/bjet.12471.

Pi, Z., Zhang, Y., Zhu, F., Xu, K., Yang, J., & Hu, W. (2019). Instructors' pointing gestures improve learning regardless of their use of directed gaze in video lectures. *Computers & Education, 128*, 345–352. https://doi.org/10.1016/j.compedu.2018.10.006.

Ping, R. M., & Goldin-Meadow, S. (2010). Gesturing saves cognitive resources when talking about nonpresent objects. *Cognitive Science, 34*(4), 602–619. https://doi.org/10.1111/j.1551-6709.2010.01102.x.

Ploetzner, R., & Fillisch, B. (2017). Not the silver bullet: Learner-generated drawings make it difficult to understand broader spatiotemporal structures in complex animations. *Learning and Instruction, 47*, 13–24. https://doi.org/10.1016/j.learninstruc.2016.10.002.

Pothier, K., & Bherer, L. (2016). Physical training. In T. Strobach & J. Karbach (Eds.), *Cognitive training: An overview of features and applications* (pp. 145–153). Cham: Springer. https://doi.org/10.1007/978-3-319-42662-4_14.

Pouw, W., Mavilidi, M.-F., van Gog, T., & Paas, F. (2016). Gesturing during mental problem solving reduces eye movements, especially for individuals with lower visual working memory capacity. *Cognitive Processing, 17*(3), 269–277. https://doi.org/10.1007/s10339-016-0757-6.

Press, C., Bird, G., Flach, R., & Heyes, C. (2005). Robotic movement elicits automatic imitation. *Cognitive Brain Research, 25*(3), 632–640. https://doi.org/10.1016/j.cogbrainres.2005.08.020.

Risko, E. F., & Gilbert, S. J. (2016). Cognitive offloading. *Trends in Cognitive Sciences, 20*(9), 676–688. https://doi.org/10.1016/j.tics.2016.07.002.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience, 27*, 169–192. https://doi.org/10.1146/annurev.neuro.27.070203.144230.

Roberts, J. R., Hagedorn, E., Dillenburg, P., Patrick, M., & Herman, T. (2005). Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course. *Biochemistry and Molecular Biology Education, 33*(2), 105–110. https://doi.org/10.1002/bmb.2005.494033022426.

Shepard, R. N., & Feng, C. (1972). A chronometric study of mental paper folding. *Cognitive Psychology, 3*(2), 228–243. https://doi.org/10.1016/0010-0285(72)90005-9.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701–703. https://doi.org/10.2307/1731476.

Skulmowski, A., Pradel, S., Kühnert, T., Brunnett, G., & Rey, G. D. (2016). Embodied learning using a tangible user interface: The effects of haptic perception and selective pointing on a spatial learning task. *Computers & Education, 92–93*, 64–75. https://doi.org/10.1016/j.compedu.2015.10.011.

So, W.-C., Shum, P. L.-C., & Wong, M. K.-Y. (2015). Gesture is more effective than spatial language in encoding spatial information. *The Quarterly Journal of Experimental Psychology, 68*(12), 2384–2401. https://doi.org/10.1080/17470218.2015.1015431.

Stieff, M., Lira, M. E., & Scopelitis, S. A. (2016). Gesture supports spatial thinking in STEM. *Cognition and Instruction, 34*(2), 80–99. https://doi.org/10.1080/07370008.2016.1145122.

Stull, A. T., & Hegarty, M. (2016). Model manipulation and learning: Fostering representational competence with virtual and concrete models. *Journal of Educational Psychology, 108*(4), 509–527. https://doi.org/10.1037/edu0000077.

Stull, A. T., & Mayer, R. E. (2007). Learning by doing versus learning by viewing: Three experimental comparisons of learner-generated versus author-provided graphic organizers. *Journal of Educational Psychology, 99*(4), 808–820. https://doi.org/10.1037/0022-0663.99.4.808.

Stull, A. T., Hegarty, M., & Mayer, R. E. (2009). Getting a handle on learning anatomy with interactive three-dimensional graphics. *Journal of Educational Psychology, 101*(4), 803–816. https://doi.org/10.1037/a0016849.

Stull, A. T., Barrett, T., & Hegarty, M. (2013). Usability of concrete and virtual models in chemistry instruction. *Computers in Human Behavior, 29*(6), 2546–2556. https://doi.org/10.1016/j.chb.2013.06.012.

Stull, A. T., Fiorella, L., Gainer, M. J., & Mayer, R. E. (2018a). Using transparent whiteboards to boost learning from online STEM lectures. *Computers & Education, 120*, 146–159. https://doi.org/10.1016/j.compedu.2018.02.005.

Stull, A. T., Fiorella, L., & Mayer, R. E. (2018b). An eye-tracking analysis of instructor presence in video lectures. *Computers in Human Behavior, 88*, 263–272. https://doi.org/10.1016/j.chb.2018.07.019.

Stull, A. T., Gainer, M. J., & Hegarty, M. (2018c). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction, 55*, 80–92. https://doi.org/10.1016/j.learninstruc.2017.09.008.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York: Springer.

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive architecture and instructional design: 20 years later. *Educational Psychology Review, 31*(2), 261–292. https://doi.org/10.1007/s10648-019-09465-5.

Tang, M., Ginns, P., & Jacobson, M. J. (2019). Tracing enhances recall and transfer of knowledge of the water cycle. *Educational Psychology Review, 31*(2), 439–455. https://doi.org/10.1007/s10648-019-09466-4.

Trewartha, K. M., Case, S., & Flanagan, J. R. (2015). Integrating actions into object location memory: A benefit for active versus passive reaching movements. *Behavioural Brain Research, 279*, 234–239. https://doi.org/10.1016/j.bbr.2014.11.043.

Vallée-Tourangeau, F., Sirota, M., & Vallée-Tourangeau, G. (2016). Interactivity mitigates the impact of working memory depletion on mental arithmetic performance. *Cognitive Research: Principles and Implications, 1*(1), 26. https://doi.org/10.1186/s41235-016-0027-2.

van Gog, T. (2014). The signaling (or cueing) principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2nd ed., pp. 263–278). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.014.

van Wermeskerken, M., Ravensbergen, S., & van Gog, T. (2018). Effects of instructor presence in video modeling examples on attention and learning. *Computers in Human Behavior, 89*, 430–438. https://doi.org/10.1016/j.chb.2017.11.038.

Voyer, D., & Jansen, P. (2016). Sex differences in chronometric mental rotation with human bodies. *Psychological Research, 80*(6), 974–984. https://doi.org/10.1007/s00426-015-0701-x.

Voyer, D., & Jansen, P. (2017). Motor expertise and performance in spatial tasks: A meta-analysis. *Human Movement Science, 54*, 110–124. https://doi.org/10.1016/j.humov.2017.04.004.

Wang, H., Pi, Z., & Hu, W. (2019). The instructor's gaze guidance in video lectures improves learning. *Journal of Computer Assisted Learning, 35*(1), 42–50. https://doi.org/10.1111/jcal.12309.

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition, 68*(1), 77–94. https://doi.org/10.1016/S0010-0277(98)00032-8.

Wiley, J. (2019). Picture this! Effects of photographs, diagrams, animations, and sketching on learning and beliefs about learning from a geoscience text. *Applied Cognitive Psychology, 33*(1), 9–19. https://doi.org/10.1002/acp.3495.

Wittrock, M. C. (1989). Generative processes of comprehension. *Educational Psychologist, 24*(4), 345–376. https://doi.org/10.1207/s15326985ep2404_2.

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of Experimental Psychology: Human Perception and Performance, 24*(2), 397–412. https://doi.org/10.1037/0096-1523.24.2.397.

Wong, A., Marcus, N., Ayres, P., Smith, L., Cooper, G. A., Paas, F., et al. (2009). Instructional animations can be superior to statics when learning human motor skills. *Computers in Human Behavior, 25*(2), 339–347. https://doi.org/10.1016/j.chb.2008.12.012.

Wouters, P., Paas, F., & van Merriënboer, J. J. G. (2008). How to optimize learning from animated models: A review of guidelines based on cognitive load. *Review of Educational Research, 78*(3), 645–675. https://doi.org/10.3102/0034654308320320.

Wu, Y. C., & Coulson, S. (2014). Co-speech iconic gestures and visuo-spatial working memory. *Acta Psychologica, 153*, 39–50. https://doi.org/10.1016/j.actpsy.2014.09.002.

Wu, S. P. W., & Rau, M. A. (2018). Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations. *Learning and Instruction, 55*, 93–104. https://doi.org/10.1016/j.learninstruc.2017.09.010.

Yammine, K., & Violato, C. (2016). The effectiveness of physical models in teaching anatomy: A meta-analysis of comparative studies. *Advances in Health Sciences Education, 21*(4), 883–895. https://doi.org/10.1007/s10459-015-9644-7.

Chapter 8
VAR: A Battery of Computer-Based Instruments to Measure Visuospatial Processing

Juan C. Castro-Alonso, Paul Ayres, and Fred Paas

Visuospatial processing is important to learn and succeed in health and natural science disciplines (see Castro-Alonso and Uttal this volume, Chap. 3). This importance is observed in science learning scenarios with visualizations (see Castro-Alonso et al. this volume-a, Chap. 5), interactive multimedia (see Castro-Alonso and Fiorella this volume, Chap. 6), and when object manipulations and gestures are involved (see Castro-Alonso et al. this volume-b, Chap. 7; see also Castro-Alonso et al. 2015). Moreover, visuospatial processing can be affected by the gender of the students (see Castro-Alonso and Jansen this volume, Chap. 4; see also Castro-Alonso et al. 2019b) and by the design of the learning materials (see Castro-Alonso et al. this volume-a, Chap. 5).

This evidence of showing that diverse phenomena depend on visuospatial processing can be partially attributed to the fact that visuospatial processing is not a single construct, but many. Hence, there is a need for instruments capable of measuring each construct when required. Although a number of different instruments are available (see Castro-Alonso and Atit this volume, Chap. 2), we have recently developed a flexible and comprehensive computer-based battery of tests that can be tailored accordingly to individual needs (see also Castro-Alonso et al. 2018a). This battery, which can be used upon request by interested researchers and practitioners, is called *VAR* (*visuospatial adaptable resources*).

J. C. Castro-Alonso (✉)
Center for Advanced Research in Education, Universidad de Chile, Santiago, Chile
e-mail: jccastro@ciae.uchile.cl

P. Ayres
School of Education, University of New South Wales, Sydney, Australia

F. Paas
Department of Psychology, Education, and Child Studies, Erasmus University Rotterdam, Rotterdam, The Netherlands

School of Education/Early Start, University of Wollongong, Wollongong, Australia

J. C. Castro-Alonso (ed.), *Visuospatial Processing for Education in Health and Natural Sciences*, https://doi.org/10.1007/978-3-030-20969-8_8

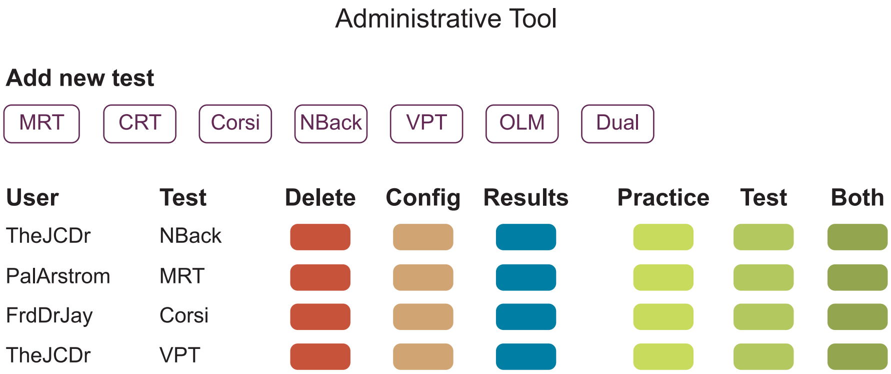
The present chapter has two main aims. First, to describe the Internet administrative tool that manages these computer-based instruments measuring visuospatial processing. Second, to describe each of these instruments and the variables that can be adjusted to suit different needs. The tests are categorized as: (a) mental rotation instruments, including a three-dimensional (3D) and a two-dimensional (2D) instrument; (b) spatial working memory instruments, which focus on the spatial processing of the visuospatial working memory processor; (c) visual working memory instruments, which focus on the visual processing of the visuospatial processor; and (d) dual visuospatial instruments of working memory, which require the simultaneous memorization and processing of visuospatial stimuli.

8.1 Administrative Tool to Manage the Instruments in VAR

The administrative tool and all the instruments were programmed in JavaScript™, so they can be used in any device that can be connected to the Internet, including desktop computers, laptops, tablets, and mobile phones. The administrative website is shown in Fig. 8.1.

As presented in Fig. 8.1, when the administrative site is accessed, a new instrument can be added by clicking on its name. Then, this test can be configured to adjust its properties to the users' needs, including difficulty level, speed, color, sounds, instructions, and language (English and Spanish currently available). Also, many other variables can be adjusted, which depends on each test. As easy as the test can be added to the administrative tool, it can also be deleted pressing another on-screen button.

After configuring the instrument, it can be decided what type of task will be completed, whether (a) practice, (b) test, or (c) both practice and test. After these are achieved, the results of the tests are automatically saved on the database, which can be accessed with a password and exported to a spreadsheet for analyses. Typical



Administrative Tool

Add new test

MRT CRT Corsi NBack VPT OLM Dual

User	Test	Delete	Config	Results	Practice	Test	Both
TheJCDr	NBack	🟥	🟫	🟦	🟩	🟩	🟩
PalArstrom	MRT	🟥	🟫	🟦	🟩	🟩	🟩
FrdDrJay	Corsi	🟥	🟫	🟦	🟩	🟩	🟩
TheJCDr	VPT	🟥	🟫	🟦	🟩	🟩	🟩

Fig. 8.1 A view of the administrative Internet tool, simplified for clarity

results that are recorded include configuration of the instruments, scoring, percentage correct, and time. However, as described next, each tool has its own set of variables that can be adjusted and results that can be measured.

8.2 Mental Rotation Instruments

Ekstrom et al. (1976) define mental rotation as the ability to process a whole shape and rotating it in the mind. As described in Castro-Alonso and Atit (this volume, Chap. 2), there are tests measuring 3D and 2D mental rotations. The 3D instruments imply rotations with 3D shapes, thus involving three axes of rotation, whereas the 2D instruments imply rotations with 2D shapes and only require two axes of rotation. As described next, the present computer battery includes a 3D instrument (Mental Rotations Test) and a 2D instrument (Card Rotations Test).

8.2.1 Mental Rotations Test

The seminal study of mental rotation by Shepard and Metzler (1971) employed abstract 3D shapes, which resemble current Tetris™ videogame blocks. The Mental Rotations Test developed by Vandenberg and Kuse (1978) incorporated similar abstract figures made of ten connected cubes. Peters et al. (1995) updated the test to the instrument that is mostly employed presently. Both of these later versions are pen-and-paper tests, but present reports have also used computer formats (e.g., Butler et al. 2006; Chu and Kita 2008; Doyle et al. 2016; Roach et al. 2019; Stull and Hegarty 2016; Wright et al. 2008).

In every item of the Mental Rotations Test, participants compare one 3D shape to four different versions displayed alongside. The task is to mark which two of these four depictions are the rotated versions of the 3D shape, thus leaving blank the other two alternatives, which are rotated and mirrored depictions (see Fig. 4.1a in Castro-Alonso and Jansen this volume, Chap. 4).

The Mental Rotations Test is so popular that it is arguably the most common test used to measure visuospatial processing. It has been employed in many studies related to health sciences, including: (a) anatomy (Garg et al. 2001; Guimarães et al. 2019; Jang et al. 2017; Loftus et al. 2017; Stull et al. 2009); (b) surgery (Keehner et al. 2006; Stransky et al. 2010; Wanzel et al. 2002); and (c) dentistry (Hegarty et al. 2009; Kozhevnikov et al. 2013). It has also been used in natural science education, covering areas such as: (a) veterinary anatomy (Gutierrez et al. 2017); (b) zoology (Imhof et al. 2011, 2012); (c) general chemistry (S. P. W. Wu and Rau 2018); (d) organic chemistry (Barrett and Hegarty 2016; Stull et al. 2018a, b); (e) geology (Atit et al. 2013; Resnick and Shipley 2013); and (f) physics (Hegarty and Sims 1994; Kozhevnikov and Thornton 2006; Peters et al. 1995). It has also been extensively used in research about sex and gender differences on mental rotation (e.g., Courvoisier et al. 2013; Heil et al. 2012; Jansen et al. 2016; McGlone and Aronson 2006; Miller and Halpern 2013; Moè et al. 2018; Vuoksimaa et al. 2010).

The computer version developed for our VAR was based on the 16 figures included in Peters and Battista (2008). Our instrument provides a choice of the 3D figures from those 16 options, and allows modifying how to display them in the test. An example of the figures selected is provided in Fig. 8.2.

Further customization of the current instrument is to adjust how, per item, each selected shape can be shown in any of the possible X, Y, Z axes of rotation (see Fig. 8.3). Other variables that can be configured are: (a) showing either plain or checkered figures; (b) the number of total items in the test; and (c) the total duration of the test.

Based on the literature (e.g., Goldstein et al. 1990; Masters 1998; Voyer and Hou 2006), we included two measures to calculate the score in the test. First, the *stringent score* of the original pen-and-paper test by Vandenberg and Kuse (1978) was included, which awards one point per item only if *both* rotated depictions are selected (while both rotated–mirrored representations are left unselected). Second, the *raw score* was considered, which awards one point per correct depiction, thus allowing two points per item.

When the test is finished, the administrative tool automatically stores which depictions were included and how they were shown, the answers of the participants (compared with the correct answers), the total scores and percentages correct (both stringent and raw measures), and the time taken to solve the test.

8.2.2 *Card Rotations Test*

The original pen-and-paper Card Rotations Test was developed by Ekstrom et al. (1976). In every item of the test, participants compare one abstract 2D shape to eight different versions at its side. The participants must discriminate between the mirrored-rotated and the rotated 2D shapes (see Fig. 4.1b in Castro-Alonso and Jansen this volume, Chap. 4).

Many health science and biology studies have employed this test, including the topics of medicine examinations (Kalet et al. 2012), the human respiratory system

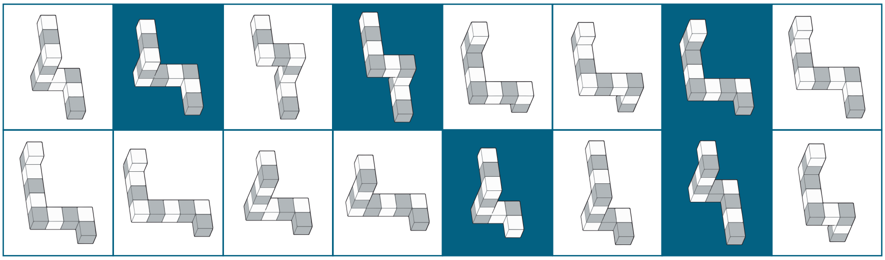
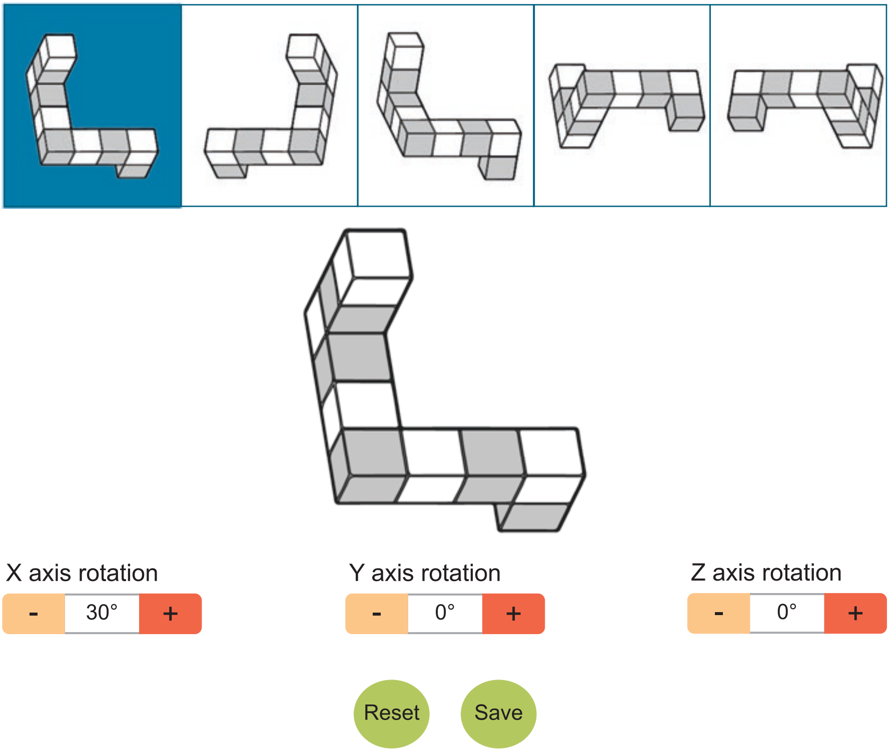


Fig. 8.2 Selection of five 3D figures from the 16 different options for the Mental Rotations Test



X axis rotation 30°

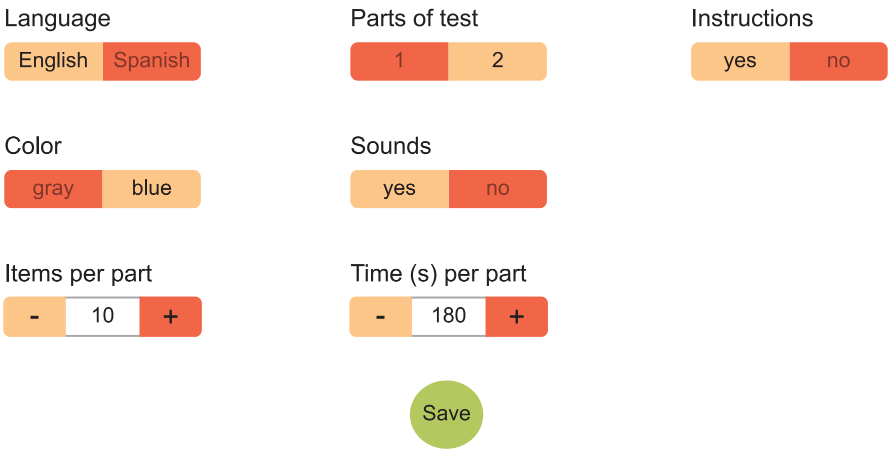
Y axis rotation 0°

Z axis rotation 0°

Fig. 8.3 Configuration of the figures for an item of the Mental Rotations Test

(Mayer and Sims 1994), and the function of the enzyme ATP-Synthase (Seufert et al. 2009). The test has also been linked to the understanding of volcanic eruptions (Sanchez 2012) and the more abstract tasks of memorizing colored symbols (Castro-Alonso et al. 2014, 2018b).

The instrument in the current battery allows selecting from 40 figures, including 20 modern versions of the original pen-and-paper 2D figures by Ekstrom et al. (1976) and the 20 novel 2D shapes reported in Castro-Alonso et al. (2018a). Settings include which figures are used, in which order, and how they are rotated and reflected. As shown in Fig. 8.4, many other variables can be adjusted, for examples, the color of the figures (gray or blue), how many parts are in the test, how many items are shown per part, and how long does each part last. When the test is ended, the system records the configuration employed, the answers given by the participants (compared with the correct answers), the total scores and percentages correct, and the time taken.



Items per part 10

Time (s) per part 180

Fig. 8.4 The configuration window of the Card Rotations Test

8.3 Spatial Working Memory Instruments

As described in Castro-Alonso and Atit (this volume, Chap. 2), the processing of spatial and visual stimuli in working memory is relatively independent, and there are common instruments tailored to measure these different cognitive processes. Commonly, the tests that measure spatial working memory involve the sequential presentation of visual stimuli; in contrast, tests that measure visual working memory use the simultaneous presentation of visual elements. As such, the following instruments, aimed to measure the spatial component of visuospatial working memory, can be classified as tests of sequential (and not simultaneous) visual stimuli (see also Darling et al. 2006).

8.3.1 Corsi Block Tapping Test

Corsi originally produced the Corsi Block Tapping Test (as cited in Milner 1971), based on an easier tapping test previously developed by Knox (1913; as cited in Richardson 2003). The traditional format of the instrument presents nine wooden blocks placed separately on a board (e.g., De Renzi et al. 1977; De Renzi and Nichelli 1975; Smirni et al. 1983). The experimenter, who usually seats in front of the participant, touches or taps the blocks, following a sequence. Then, the participant must repeat the tapping sequence, from memory (Ruggiero et al. 2008). In contrast to these 3D wooden blocks, contemporary adaptations use virtual versions with 2D squares on the screen (e.g., Ashkenazi and Shapira 2017; Castro-Alonso et al. 2018b; Cornoldi and Mammarella 2008; Eielts et al. 2018; Fischer 2001; Pilegard and Mayer 2018; So et al. 2015; Y. C. Wu and Coulson 2014; see also Fig. 2.5 in Castro-Alonso and Atit this volume, Chap. 2).

Increasing in difficulty, the sequences to be memorized can begin with a relatively easy 3-Square trial. An example of a 3-Square sequence would show that the squares being highlighted in order are those numbered as 2-4-7. Then, the test can increase by one square per level, and finish in the most difficult 9-Block sequence (e.g., highlighted squares are: 7-9-3-6-2-8-4-5-1). The test of the current battery can be adjusted in both the initial and the final length of the sequences. The sequences are based on those employed by Smirni et al. (1983).

In addition to changing the length of the sequences, the Corsi test can be answered using both directions: In the forward "traditional" direction, the squares must be clicked in the normal order they were presented; in contrast, in the backward test, the blocks must be clicked in the reverse order as observed (e.g., the correct answer for the sequence 1-2-3-4 is 4-3-2-1). Regarding what direction of recall should be preferred among researchers, there are advantages for either forward or backward recall. A reason to favor backward recall is that it is a task that demands not only short-term memory (as the forward direction), but also executive functioning, so it involves more working memory resources (cf. Ashkenazi and Danan 2017; Miyake et al. 2001). As the backward direction relies more on executive resources, it has also been linked more than the forward direction to mental rotation tasks (Cornoldi and Mammarella 2008). Favoring forward recall would be appropriate if an easier test is desired. The instrument included in VAR allows a choice of either forward or backward directions.

Other variables that can be customized in the Corsi of VAR are: (a) the sequences per level (e.g. for a 4-Square sequence, the user could set the sequence 5-2-7-9); (b) duration of each square being highlighted (e.g., 1,000 ms per square); and (c) showing or not showing the number on top of each square, so participants could use verbal processing (when numbers are shown) to be helped in the task.

After the participants complete the test, the system records whether the test was forward or backward, the sequences memorized (against the correct sequences), the scores and percentages of accuracy (per level and in total), the time taken to start each answer, and the entire time taken for the test.

8.3.2 Spatial N-Back Task

The original n-back tests were developed by Kirchner (1958) with sequences of physical flashing lights. Nowadays, the test is typically conducted in computer versions, where verbal or visuospatial stimuli is used (e.g., Hautzel et al. 2002; Lejbak et al. 2011; Nystrom et al. 2000; see also Au et al. 2015; Dougherty et al. 2016).

The task in any n-back test is to determine if a given stimulus has already been shown. As an example, Fig. 8.5 depicts the Spatial 3-Back Task that is included in VAR. As the figure shows, the first screen depicts Stimulus X, which disappears after an interval, and gives place to Stimulus Y, which also disappears after the same given interval, to give place to Stimulus Z. Then, the Test Stimulus is presented, when the participant must answer if this test depiction is the same or not as Stimulus X, the first stimulus shown 3-back ago displays.

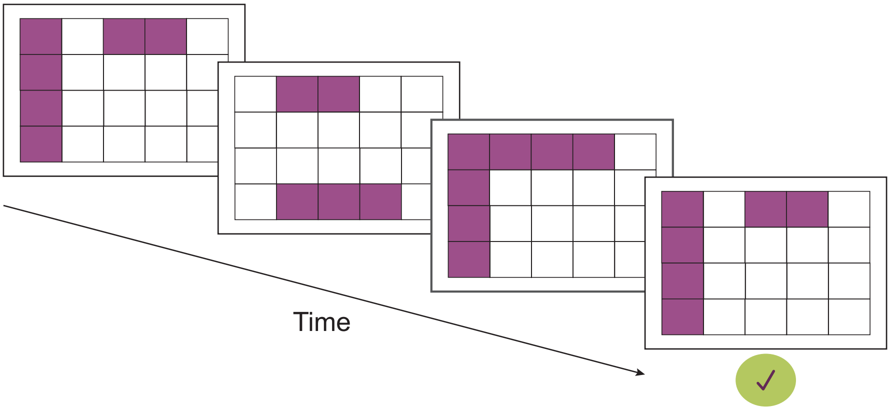


Fig. 8.5 A spatial 3-bak task showing a correct answer

There are several ways to change the difficulty of a spatial n-back task. In addition, to a 2-back level, the test can be increased in difficulty by including 3-back levels (e.g., Lavric et al. 2003; McEvoy et al. 1998; Schmiedek et al. 2009; Shackman et al. 2006) or even more, such as 8-back options (e.g., Schwarb et al. 2016). Another way to make the test more difficult is by showing more complex visuospatial stimuli. For example, customary displays in the n-back tests are patterns of filled and empty squares. In these designs, difficulty could be increased from, for example, a 3 × 3 pattern of nine squares (e.g., Li et al. 2008; Minear et al. 2016; Stephenson and Halpern 2013), to patterns of 4 × 3 (McEvoy et al. 1998), 4 × 4 (Schmiedek et al. 2009), 5 × 4 (Lejbak et al. 2011), or 5 × 5 arrays (Schwarb et al. 2016). Also, less regular patterns entail more visual complexity (e.g., Lavric et al. 2003; Nystrom et al. 2000; Shackman et al. 2006). Moreover, another way to make the test more difficult is to show each stimulus for a briefer time (e.g., Schmiedek et al. 2009) or using long blank intervals between the stimuli. These options to adjust the level of difficulty of the Spatial N-Back Task are allowed in the test included in our battery.

Other variables that can be adapted by the present instrument are: (a) the number of trials per level (e.g., four trials); and (b) displaying or not the number on top of each square in order to include verbal processing (in the case of showing the numbers).

After completing the Spatial N-Back Task, the database automatically stores the configurations used, the answers of the participants (compared with the correct answers), the scores and percentages correct (per level and in total), and the total time taken for the whole test.

8.4 Visual Working Memory Instruments

The following instruments, which are aimed to measure the visual processing in working memory, can be classified as instruments showing simultaneous (and not sequential) visual stimuli (see Darling et al. 2006; see also Rudkin et al. 2007).

8.4.1 Visual Patterns Test

The Visual Patterns Test was published by Della Sala et al. (1999), based on previous instruments reported by Phillips and Baddeley (1971). The test shows patterns of squares, for example, a grid of 25 squares in a 5 × 5 configuration. Randomly, half of the squares are filled, and half are blank. The aim of the test is to memorize which are the filled squares, and then from memory replicate this pattern on an empty test configuration.

The complexity of the instrument can be increased by adding more squares to be remembered (e.g., Eielts et al. 2018; Pouw et al. 2016; Wilson et al. 1987). The Visual Patterns Test in the present battery, as in Della Sala et al. (1999), begins with easier configurations of four squares (2 × 2 patterns) and increases difficulty until reaching the most difficult arrangement of 30 squares (6 × 5 patterns; see also Fig. 2.6 in Castro-Alonso and Atit this volume, Chap. 2).

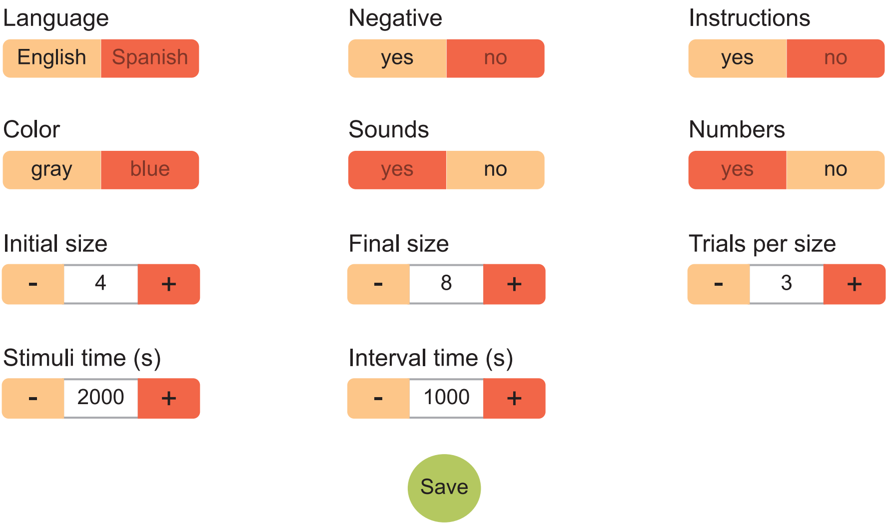
In the seminal study by Della Sala et al. (1999), it was reported that the goal of this instrument was to measure to a greater extent the visual component of working memory, to distinguish this test from other tools that focus on measuring the spatial component. For example, Della Sala and colleagues conducted an experiment with 16 undergraduates (44% females), in which a visual and a spatial test were used. The findings showed that the visual test selectively interfered with the Visual Patterns Test, but not the spatial test. In contrast, the spatial test selectively interfered with the Corsi Block Tapping Test, but not the visual test. In these results of double dissociations, it was concluded that the Visual Patterns Test was more effective to measure the visual component of working memory, whereas the Corsi Block Tapping Test was a more appropriate measure for the spatial component.

As shown in Fig. 8.6, the version of the test included in VAR allows adaptation of the: (a) stimuli time to present each pattern (e.g., 2,000 ms); (b) interval time with a blank display (e.g., 1,000 ms); (c) number of trials per configuration (e.g. three trials); (d) possibility of doing a “negative” version, in which the empty squares must be answered as filled, and vice versa; and (e) possibility of showing or not the number of each square, so participants could be aided by verbal tags.

After the test is ended, the system automatically records whether the test was negative or positive, the answers of the participants (compared with the correct answers), the scores and percentages correct (per level and in total), and the entire time of testing.

8.4.2 Object Location Memory and Object Identity Memory

The classic studies measuring Object Location Memory and Object Identity Memory (e.g., Eals and Silverman 1994; see also Epting and Overman 1998) employed pen-and-paper instruments, but more recent versions are using computers (e.g., Postma et al. 2004). An interesting finding of these tasks, either in paper or computer versions, concerns gender differences (see Castro-Alonso and Jansen this



Initial size 4

Final size 8

Trials per size 3

Stimuli time (s) 2000

Interval time (s) 1000

Fig. 8.6 The configuration window of the Visual Patterns Test

volume, Chap. 4). Usually, visuospatial processing instruments, such as those in VAR, show that men tend to outperform women. This outcome is particularly evident in the Mental Rotations Test (see Masters and Sanders 1993; Silverman et al. 2007). However, Object Location Memory, and to a smaller extent Object Identify Memory, tend to show the opposite results in which females surpass males (e.g., Eals and Silverman 1994; Silverman et al. 2007; but see Epting and Overman 1998).

The instruments developed for this battery were based on the *Object Relocation* test presented in Kessels et al. (1999) and Postma et al. (2004). In the Object Location Memory task, for a stimuli time of a set duration, a display of visual elements is presented on a square grid (a single element per cell on the grid). After a predetermined interval, at test time, the elements are presented beside the grid (in a random distribution) and must be placed, from memory, in the original positions (see Fig. 8.7).

The Object Identity Memory task of the current battery is similar. In this test, an analogous visual array is presented for a certain amount of stimuli time. After a specified blank interval, a test display is shown. It must be judged if the same elements were shown in both displays or if some of these elements were changed between the arrays (see Fig. 8.8).

To investigate if verbal processing is used in these tasks, we designed both concrete and abstract illustrations. These two types of drawings can be used as the visual elements in the grid cells. The rationale of using these types is that concrete elements can be memorized with the aid of verbal strategies better than abstract elements, and these strategies sometimes show gender differences (e.g., Choi and L'Hirondelle 2005).

To design the concrete elements, we adapted the clipart illustrations by Saryazdi et al. (2018). We chose clipart illustrations over real photographs, as the authors reported that 240 adults attributed higher familiarity ratings to illustrations than

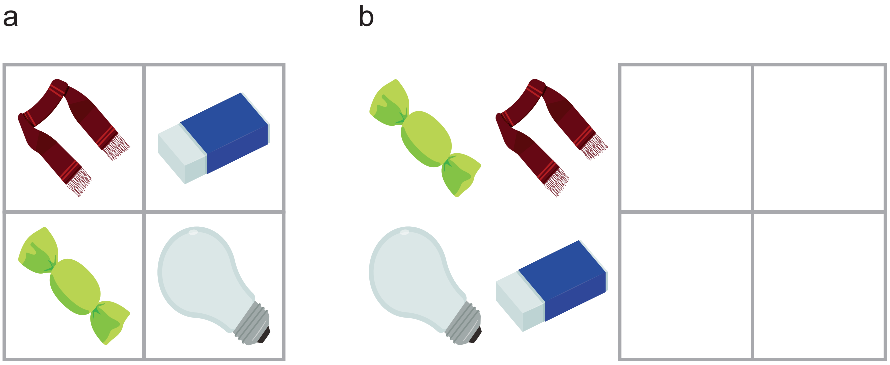


Fig. 8.7 An Object Location Memory trial of the smallest size (2 × 2 cells), including only concrete illustrations. The figure shows the beginning of (**a**) stimuli time, and (**b**) test time

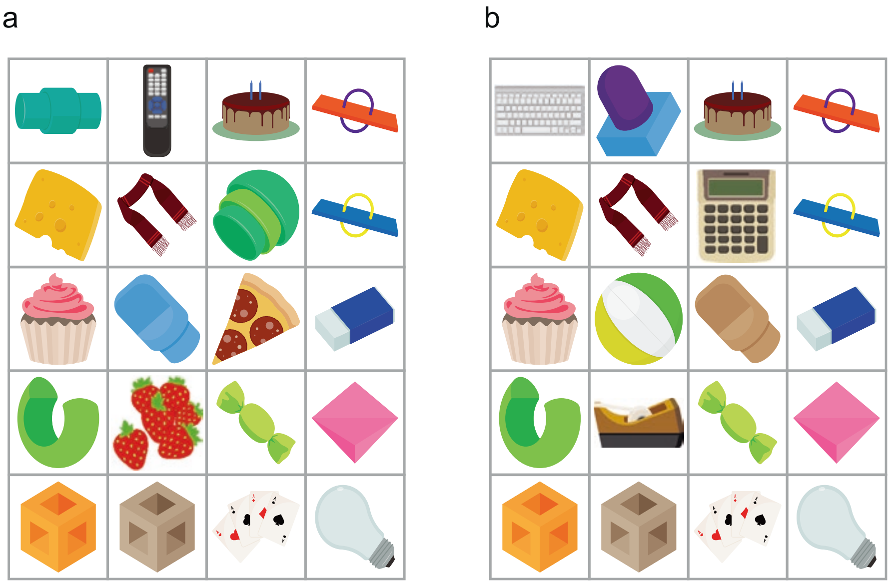


Fig. 8.8 An Object Identity Memory trial of medium size (4 × 5 cells), including concrete and abstract illustrations. The figure shows the beginning of (**a**) stimuli time, and (**b**) test time

photos. From the 17 categories containing 225 illustrations of everyday objects, we chose the eight categories with most elements, namely: *food*, *kitchen item*, *school/office supply*, *toy*, *electronic*, *household article*, *clothing*, and *bathroom item*. We then discarded all illustrations with a familiarity value below the median of the whole set of 225 illustrations. Then, all elements were simplified by reducing their visual components. This resulted in a final collection of 99 concrete drawings (see examples in Figs. 8.7 and 8.8).

To design the abstract elements, 50 non-existing objects were created with a similar appearance to the concrete and real elements. As these abstract elements had two color versions, a total of 100 abstract illustrations were designed (see examples in Fig. 8.8). In total, there are currently 99 (concrete) + 100 (abstract) = 199 visual elements to use in the Object Location Memory and Object Identity Memory tasks included in VAR.

Also, the difficulty of the tests can be increased by enlarging the grids. As such, the grids can include 2–7 columns and 2–5 rows. Thus, the easiest grid is a 2 × 2 array containing four cells with elements and the most difficult is a 7 × 5 array including 35 different items. Also, both instruments allow adapting: (a) time to present the grid (e.g., 50,000 ms); (b) blank interval time (e.g., 5,000 ms); (c) number of trials (e.g. two trials); and (d) whether the lines of the grid are shown or not shown.

Consistent with previous studies (e.g., Choi and L'Hirondelle 2005; Hammond et al. 2019; Kessels et al. 1999; Nairne et al. 2012; Postma et al. 2004), we devised two measures to calculate the score in the Object Location Memory task: (a) a *displacement error* or *distance error*, which has more fine-grained scoring by punishing answers further away from the correct answer; and (b) a *hit/miss score*, which has coarser scoring by giving zero points to any incorrectly placed element (irrespective of its position), and one point for any correctly placed element. For the Object Identity Memory task, the hit/miss score was employed.

After the Object Location Memory or the Object Identity Memory tasks are finished, the system automatically records the size of the grid and which figures were used (concrete and/or abstract), the presentation and interval times employed, user answers (compared with the correct answers), the scores and percentages correct (both distance error and hit/miss measures), and the total time taken.

8.5 Dual Visuospatial Instruments of Working Memory

These dual or complex working memory instruments include a *memory task* that is interrupted by a *processing task*. For example, the original test of this type was developed by Daneman and Carpenter (1980) and called the *Reading Span Task*. In this dual verbal task, the memory task was to remember the last words from a sequence of sentences, while reading or listening (the processing task) to these sentences. Hence, reading and listening were processing activities that interrupted the memorizing of the last words in the order presented.

From this inception, several verbal and visuospatial dual working memory tasks have been developed. For example, six common visuospatial instruments are called: (a) the *Counting Span* (e.g., Kane et al. 2004; Schmiedek et al. 2009), (b) the *Rotation Span* (e.g., Foster et al. 2017; Miller and Halpern 2013; Shah and Miyake 1996), (c) the *Symmetry Span* (e.g., Kane et al. 2004; Minear et al. 2016; Schwaighofer et al. 2016), (d) the *Rotation-Matrix Span* (e.g., Blalock and McCabe 2011), (e) the *Alignment Span* (e.g., Hale et al. 2011; Minear et al. 2016), and (f) the *Dot Matrix Task* (e.g., Giofrè et al. 2018; Miyake et al. 2001; Örün and Akbulut 2019).

The dual visuospatial tasks of working memory developed for VAR (see also Castro-Alonso et al. 2018a) allow combinations of two memory and three processing tasks from those published tests. The two memory tasks included are: (a) *Matrix Positions*, and (b) *Rotated Arrows*. The stimuli to memorize in the former are matrices of squares highlighted in different positions. The stimuli to memorize in the latter are arrows shown in different rotational degrees.

The three processing tasks included in this battery are: (a) *Symmetry Patterns*, (b) *Visual* Equations, and (c) Letter *Rotations*. In Symmetry Patterns, judgments must be made on whether the display is symmetrical or asymmetrical around the Y-axis. In Visual Equations, judgments are made on whether the additions or subtractions between two dot patterns are correct or incorrect. Lastly, in Letter Rotations, it must be decided if the capital letters shown are normal or horizontally-reflected. Figure 8.9 shows a dual visuospatial working memory trial in which the memory task employed was Matrix Positions and the processing task was Symmetry Patterns.

Other variables that can be adjusted in these tasks include: (a) time to present the stimuli (e.g., 1,500 ms); (b) inter-stimuli lapse with a blank display (e.g., 500 ms); (c) starting and ending difficulty levels; and (d) number of trials per level.

Unsworth et al. (2005) recommended using both the memory and the processing tasks when scoring these dual instruments. Hence, in VAR, both memory and processing tasks are scored. For the memory tasks, each correctly memorized element is scored one point. This implies memorizing: (a) the correct element,

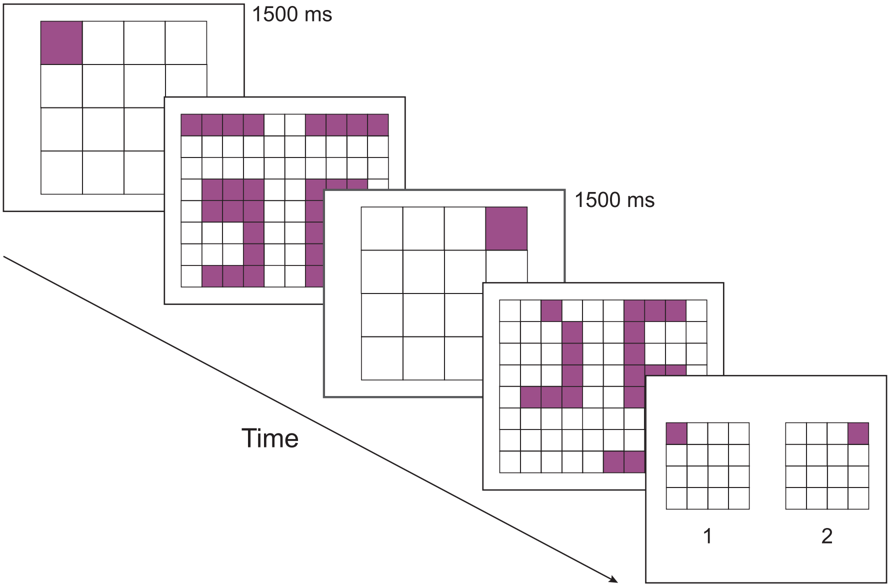


Fig. 8.9 A trial for a dual visuospatial task of working memory in which the selected memory task was Matrix Positions, and the selected processing task was Symmetry Patterns. The correct answer for Matrix Positions is shown. Note that the test has been simplified for clarity

and (b) the correct order presented. For the processing task, each correctly processed item is also awarded one point.

After the test is completed, the system records the memory and processing tasks used, the presentation and interval times employed, the answers of the participants (compared with the correct answers), the actual scores and the percentages correct (per level and in total), and the total time taken.

8.6 Discussion

Visuospatial processing entails different visual and spatial abilities that can help learning in diverse situations. There is a current need to investigate the direct relationships between these abilities and academic achievement in diverse health and natural sciences (see also Castro-Alonso et al. 2019a). To examine these relationships, we have developed VAR (visuospatial adaptable resources), a battery of computer instruments that measure different aspects of visuospatial processing.

VAR contains seven Internet instruments, including two mental rotation tests, two spatial and two visual working memory tests, and dual visuospatial working memory tasks. The mental rotation tests are a 3D instrument based on the Mental Rotations Test, and a 2D test based on the Card Rotations Test. For the two spatial working memory instruments of sequential stimuli, one is based on the Corsi Block Tapping Test, and the other one follows the n-back paradigm. Regarding the two visual working memory instruments of simultaneous stimuli, one is an adaptation of the Visual Patterns Test, and the other one is based on Object Location Memory and Object Identity Memory tasks. Lastly, the dual visuospatial tasks of working memory can be constructed from two different memory tasks and three different processing tasks.

An Internet administrative tool, with restricted access, gives the user the control to configure the tests. Some of the variables that can be changed are whether including or excluding practices before the tests, the language of the instructions and the written information (English and Spanish), the starting and ending difficulty levels, and the timing of the tasks. Importantly, this administrative tool automatically saves the data of the completed tests so that this information can be easily exported to spreadsheets for further analyses.

8.6.1 Instructional Implications for Health and Natural Sciences

A first instructional implication concerns measuring different visuospatial processes with various instruments of this battery. Also, the relationships between these different abilities can be calculated. The data provided could help teachers and instructional designers to get a detailed evaluation of the visuospatial abilities of their students.

A second implication is related to the possibility of using VAR to predict potential difficulties that their users might face. For example, there could be a Mental Rotations Test score threshold that must be reached before achieving acceptable levels of mastery in a specific science discipline, such as anatomy (see Guillot et al. 2007). Hence, fast-paced tests might facilitate this knowledge faster.

A third implication is related to visuospatial training (see Stieff and Uttal 2015; see also Castro-Alonso and Uttal this volume, Chap. 3). If low visuospatial processing may negatively affect learning a specific science topic, then completing practice exercises from the instruments in VAR could raise the appropriate ability levels and be potentially helpful in learning the science concept.

A fourth and last implication flows from the previous one. If there is a detailed evaluation of the visuospatial abilities of a student, including how the student responds to changes in some variables of these abilities (e.g., speed), that data would show which ability and under what circumstances are requiring remedial training.

8.6.2 Future Research Directions

A research direction that could be pursued using this VAR battery is to compare different instructional designs of specific science topics and how they are dependent upon visuospatial processing. For example, by comparing well-matched multimedia instructional materials (see Castro-Alonso et al. 2016) that differ in cognitive load demands (see Castro-Alonso et al. this volume-a, Chap. 5), it may be possible to identify the most effective instructional designs based on specific visuospatial abilities.

Also, as recent findings (e.g., Chen et al. 2018) have shown that cognitive load can change depending on timing factors, different visuospatial abilities could be more or less affected by these timing relationships. For example, it could be investigated if the known relationship between anatomy learning and mental rotation is affected when more simultaneous mental rotations or visual working memory processes are involved.

Another suggestion for research comprises investigating the relationship between a specific visuospatial ability and a specific science discipline or topic. For example, there is an agreement in the usefulness of 3D mental rotation to learn some topics of human anatomy (e.g., Guillot et al. 2007; Lufler et al. 2012; Stull et al. 2009) and organic chemistry (Barrett and Hegarty 2016; Stull and Hegarty 2016). However, results are less conclusive for other visuospatial abilities (e.g., spatial working memory) and other disciplines (e.g., biology, cf. Castro-Alonso and Uttal 2019).

8.6.3 Conclusion

We developed VAR, a battery of seven computer-adaptable Internet instruments to measure different aspects of visuospatial processing. The tests are two mental rotation instruments, two spatial working memory tests, two visual working memory tests, and a dual visuospatial task of working memory. Also, an administrative tool has been created to allow customization of the instruments and recording of their generated data. Researchers and practitioners in health and natural sciences could employ these Internet instruments to measure the visuospatial abilities of participants and students accurately. Furthermore, VAR can be used as a research tool to investigate which specific visual or spatial ability is most relevant for a particular learning topic (e.g., molecular representations) or discipline (e.g., anatomy, surgery). Finally, as the instruments can be customized in several ways, different phenomena associated with mental rotation, spatial ability, and visuospatial working memory could be investigated.

Acknowledgments Support from PIA–CONICYT Basal Funds for Centers of Excellence Project FB0003, and CONICYT Fondecyt 11180255, is gratefully acknowledged. The first author is thankful to Mariana Poblete and Monserratt Ibáñez for their assistance, and to Mauricio Barrios and Juan Pablo Torres for helping with the illustrations.

References

Ashkenazi, S., & Danan, Y. (2017). The role of mathematical anxiety and working memory on the performance of different types of arithmetic tasks. *Trends in Neuroscience and Education, 7*, 1–10. https://doi.org/10.1016/j.tine.2017.05.001.

Ashkenazi, S., & Shapira, S. (2017). Number line estimation under working memory load: Dissociations between working memory subsystems. *Trends in Neuroscience and Education, 8–9*, 1–9. https://doi.org/10.1016/j.tine.2017.09.001.

Atit, K., Shipley, T. F., & Tikoff, B. (2013). Twisting space: Are rigid and non-rigid mental transformations separate spatial skills? *Cognitive Processing, 14*(2), 163–173. https://doi.org/10.1007/s10339-013-0550-8.

Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., & Jaeggi, S. M. (2015). Improving fluid intelligence with training on working memory: A meta-analysis. *Psychonomic Bulletin & Review, 22*(2), 366–377. https://doi.org/10.3758/s13423-014-0699-x.

Barrett, T. J., & Hegarty, M. (2016). Effects of interface and spatial ability on manipulation of virtual models in a STEM domain. *Computers in Human Behavior, 65*, 220–231. https://doi.org/10.1016/j.chb.2016.06.026.

Blalock, L. D., & McCabe, D. P. (2011). Proactive interference and practice effects in visuospatial working memory span task performance. *Memory, 19*(1), 83–91. https://doi.org/10.1080/09658211.2010.537035.

Butler, T., Imperato-McGinley, J., Pan, H., Voyer, D., Cordero, J., Zhu, Y.-S., et al. (2006). Sex differences in mental rotation: Top–down versus bottom–up processing. *NeuroImage, 32*(1), 445–456. https://doi.org/10.1016/j.neuroimage.2006.03.030.

Castro-Alonso, J. C., & Atit, K. (this volume). Different abilities controlled by visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 23–51). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_2.

Castro-Alonso, J. C., & Fiorella, L. (this volume). Interactive science multimedia and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 145–173). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_6.

Castro-Alonso, J. C., & Jansen, P. (this volume). Sex differences in visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 81–110). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_4.

Castro-Alonso, J. C., & Uttal, D. H. (2019). Spatial ability for university biology education. In S. Nazir, A.-M. Teperi, & A. Polak-Sopińska (Eds.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2018 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 283–291). Cham: Springer. https://doi.org/10.1007/978-3-319-93882-0_28.

Castro-Alonso, J. C., & Uttal, D. H. (this volume). Science education and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 53–79). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_3.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2014). Learning from observing hands in static and animated versions of non-manipulative tasks. *Learning and Instruction, 34*, 11–21. https://doi.org/10.1016/j.learninstruc.2014.07.005.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2015). The potential of embodied cognition to improve STEAM instructional dynamic visualizations. In X. Ge, D. Ifenthaler, & J. M. Spector (Eds.), *Emerging technologies for STEAM education: Full STEAM ahead* (pp. 113–136). New York: Springer. https://doi.org/10.1007/978-3-319-02573-5_7.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2016). Comparing apples and oranges? A critical look at research on learning from statics versus animations. *Computers & Education, 102*, 234–243. https://doi.org/10.1016/j.compedu.2016.09.004.

Castro-Alonso, J. C., Ayres, P., & Paas, F. (2018a). Computerized and adaptable tests to measure visuospatial abilities in STEM students. In T. Andre (Ed.), *Advances in human factors in training, education, and learning sciences: Proceedings of the AHFE 2017 International Conference on Human Factors in Training, Education, and Learning Sciences* (pp. 337–349). Cham: Springer. https://doi.org/10.1007/978-3-319-60018-5_33.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2018b). Learning symbols from permanent and transient visual presentations: Don't overplay the hand. *Computers & Education, 116*, 1–13. https://doi.org/10.1016/j.compedu.2017.08.011.

Castro-Alonso, J. C., Ayres, P., Wong, M., & Paas, F. (2019a). Visuospatial tests and multimedia learning: The importance of employing relevant instruments. In S. Tindall-Ford, S. Agostinho, & J. Sweller (Eds.), *Advances in cognitive load theory: Rethinking teaching* (pp. 89–99). New York: Routledge. https://doi.org/10.4324/9780429283895-8.

Castro-Alonso, J. C., Wong, M., Adesope, O. O., Ayres, P., & Paas, F. (2019b). Gender imbalance in instructional dynamic versus static visualizations: A meta-analysis. *Educational Psychology Review*, *31*(2), 361–387. https://doi.org/10.1007/s10648-019-09469-1.

Castro-Alonso, J. C., Ayres, P., & Sweller, J. (this volume-a). Instructional visualizations, cognitive load theory, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 111–143). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_5.

Castro-Alonso, J. C., Paas, F., & Ginns, P. (this volume-b). Embodied cognition, science education, and visuospatial processing. In J. C. Castro-Alonso (Ed.), *Visuospatial processing for education in health and natural sciences* (pp. 175–205). Cham: Springer. https://doi.org/10.1007/978-3-030-20969-8_7.

Chen, O., Castro-Alonso, J. C., Paas, F., & Sweller, J. (2018). Extending cognitive load theory to incorporate working memory resource depletion: Evidence from the spacing effect. *Educational Psychology Review, 30*(2), 483–501. https://doi.org/10.1007/s10648-017-9426-2.

Choi, J., & L'Hirondelle, N. (2005). Object location memory: A direct test of the verbal memory hypothesis. *Learning and Individual Differences, 15*(3), 237–245. https://doi.org/10.1016/j.lindif.2005.02.001.

Chu, M., & Kita, S. (2008). Spontaneous gestures during mental rotation tasks: Insights into the microdevelopment of the motor strategy. *Journal of Experimental Psychology: General, 137*(4), 706–723. https://doi.org/10.1037/a0013157.

Cornoldi, C., & Mammarella, I. C. (2008). A comparison of backward and forward spatial spans. *The Quarterly Journal of Experimental Psychology, 61*(5), 674–682. https://doi.org/10.1080/17470210701774200.

Courvoisier, D. S., Renaud, O., Geiser, C., Paschke, K., Gaudy, K., & Jordan, K. (2013). Sex hormones and mental rotation: An intensive longitudinal investigation. *Hormones and Behavior, 63*(2), 345–351. https://doi.org/10.1016/j.yhbeh.2012.12.007.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*(4), 450–466. https://doi.org/10.1016/S0022-5371(80)90312-6.

Darling, S., Della Sala, S., Logie, R. H., & Cantagallo, A. (2006). Neuropsychological evidence for separating components of visuo–spatial working memory. *Journal of Neurology, 253*(2), 176–180. https://doi.org/10.1007/s00415-005-0944-3.

De Renzi, E., & Nichelli, P. (1975). Verbal and non-verbal short-term memory impairment following hemispheric damage. *Cortex, 11*(4), 341–354. https://doi.org/10.1016/S0010-9452(75)80026-8.

De Renzi, E., Faglioni, P., & Previdi, P. (1977). Spatial memory and hemispheric locus of lesion. *Cortex, 13*(4), 424–433. https://doi.org/10.1016/S0010-9452(77)80022-1.

Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwelding visuo–spatial memory. *Neuropsychologia, 37*(10), 1189–1199. https://doi.org/10.1016/S0028-3932(98)00159-6.

Dougherty, M. R., Hamovitz, T., & Tidwell, J. W. (2016). Reevaluating the effectiveness of n-back training on transfer through the Bayesian lens: Support for the null. *Psychonomic Bulletin & Review, 23*(1), 306–316. https://doi.org/10.3758/s13423-015-0865-9.

Doyle, R. A., Voyer, D., & Lesmana, M. (2016). Item type, occlusion, and gender differences in mental rotation. *The Quarterly Journal of Experimental Psychology, 69*(8), 1530–1544. https://doi.org/10.1080/17470218.2015.1086807.

Eals, M., & Silverman, I. (1994). The Hunter-Gatherer theory of spatial sex differences: Proximate factors mediating the female advantage in recall of object arrays. *Ethology and Sociobiology, 15*(2), 95–105. https://doi.org/10.1016/0162-3095(94)90020-5.

Eielts, C., Pouw, W., Ouwehand, K., van Gog, T., Zwaan, R. A., & Paas, F. (2018). Co-thought gesturing supports more complex problem solving in subjects with lower visual working-memory capacity. *Psychological Research*. Advance online publication. https://doi.org/10.1007/s00426-018-1065-9.

Ekstrom, R. B., French, J. W., Harman, H. H., & Dermen, D. (1976). *Kit of factor-referenced cognitive tests*. Princeton: Educational Testing Service.

Epting, L. K., & Overman, W. H. (1998). Sex-sensitive tasks in men and women: A search for performance fluctuations across the menstrual cycle. *Behavioral Neuroscience, 112*(6), 1304–1317. https://doi.org/10.1037/0735-7044.112.6.1304.

Fischer, M. H. (2001). Probing spatial working memory with the Corsi Blocks task. *Brain and Cognition, 45*(2), 143–154. https://doi.org/10.1006/brcg.2000.1221.

Foster, J. L., Harrison, T. L., Hicks, K. L., Draheim, C., Redick, T. S., & Engle, R. W. (2017). Do the effects of working memory training depend on baseline ability level? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*(11), 1677–1689. https://doi.org/10.1037/xlm0000426.

Garg, A. X., Norman, G., & Sperotable, L. (2001). How medical students learn spatial anatomy. *The Lancet, 357*(9253), 363–364. https://doi.org/10.1016/S0140-6736(00)03649-7.

Giofrè, D., Donolato, E., & Mammarella, I. C. (2018). The differential role of verbal and visuospatial working memory in mathematics and reading. *Trends in Neuroscience and Education, 12*, 1–6. https://doi.org/10.1016/j.tine.2018.07.001.

Goldstein, D., Haldane, D., & Mitchell, C. (1990). Sex differences in visual-spatial ability: The role of performance factors. *Memory & Cognition, 18*(5), 546–550. https://doi.org/10.3758/BF03198487.

Guillot, A., Champely, S., Batier, C., Thiriet, P., & Collet, C. (2007). Relationship between spatial abilities, mental rotation and functional anatomy learning. *Advances in Health Sciences Education, 12*(4), 491–507. https://doi.org/10.1007/s10459-006-9021-7.

Guimarães, B., Firmino-Machado, J., Tsisar, S., Viana, B., Pinto-Sousa, M., Vieira-Marques, P., et al. (2019). The role of anatomy computer-assisted learning on spatial abilities of medical students. *Anatomical Sciences Education, 12*(2), 138–153. https://doi.org/10.1002/ase.1795.

Gutierrez, J. C., Chigerwe, M., Ilkiw, J. E., Youngblood, P., Holladay, S. D., & Srivastava, S. (2017). Spatial and visual reasoning: Do these abilities improve in first-year veterinary medical students exposed to an integrated curriculum? *Journal of Veterinary Medical Education, 44*(4), 669–675. https://doi.org/10.3138/jvme.0915-158R3.

Hale, S., Rose, N. S., Myerson, J., Strube, M. J., Sommers, M., Tye-Murray, N., et al. (2011). The structure of working memory abilities across the adult life span. *Psychology and Aging, 26*(1), 92–110. https://doi.org/10.1037/a0021483.

Hammond, A. G., Murphy, E. M., Silverman, B. M., Bernas, R. S., & Nardi, D. (2019). No environmental context-dependent effect, but interference, of physical activity on object location memory. *Cognitive Processing, 20*(1), 31–43. https://doi.org/10.1007/s10339-018-0875-4.

Hautzel, H., Mottaghy, F. M., Schmidt, D., Zemb, M., Shah, N. J., Müller-Gärtner, H.-W., et al. (2002). Topographic segregation and convergence of verbal, object, shape and spatial working memory in humans. *Neuroscience Letters, 323*(2), 156–160. https://doi.org/10.1016/S0304-3940(02)00125-8.

Hegarty, M., & Sims, V. K. (1994). Individual differences in mental animation during mechanical reasoning. *Memory & Cognition, 22*(4), 411–430. https://doi.org/10.3758/bf03200867.

Hegarty, M., Keehner, M., Khooshabeh, P., & Montello, D. R. (2009). How spatial abilities enhance, and are enhanced by, dental education. *Learning and Individual Differences, 19*(1), 61–70. https://doi.org/10.1016/j.lindif.2008.04.006.

Heil, M., Jansen, P., Quaiser-Pohl, C., & Neuburger, S. (2012). Gender-specific effects of artificially induced gender beliefs in mental rotation. *Learning and Individual Differences, 22*(3), 350–353. https://doi.org/10.1016/j.lindif.2012.01.004.

Imhof, B., Scheiter, K., & Gerjets, P. (2011). Learning about locomotion patterns from visualizations: Effects of presentation format and realism. *Computers & Education, 57*(3), 1961–1970. https://doi.org/10.1016/j.compedu.2011.05.004.

Imhof, B., Scheiter, K., Edelmann, J., & Gerjets, P. (2012). How temporal and spatial aspects of presenting visualizations affect learning about locomotion patterns. *Learning and Instruction, 22*(3), 193–205. https://doi.org/10.1016/j.learninstruc.2011.10.006.

Jang, S., Vitale, J. M., Jyung, R. W., & Black, J. B. (2017). Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. *Computers & Education, 106*, 150–165. https://doi.org/10.1016/j.compedu.2016.12.009.

Jansen, P., Zayed, K., & Osmann, R. (2016). Gender differences in mental rotation in Oman and Germany. *Learning and Individual Differences, 51*, 284–290. https://doi.org/10.1016/j.lindif.2016.08.033.

Kalet, A. L., Song, H. S., Sarpel, U., Schwartz, R. N., Brenner, J., Ark, T. K., et al. (2012). Just enough, but not too much interactivity leads to better clinical skills performance after a computer assisted learning module. *Medical Teacher, 34*(10), 833–839. https://doi.org/10.3109/0142159X.2012.706727.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General, 133*(2), 189–217. https://doi.org/10.1037/0096-3445.133.2.189.

Keehner, M., Lippa, Y., Montello, D. R., Tendick, F., & Hegarty, M. (2006). Learning a spatial skill for surgery: How the contributions of abilities change with practice. *Applied Cognitive Psychology, 20*(4), 487–503. https://doi.org/10.1002/acp.1198.

Kessels, R. P. C., Postma, A., & de Haan, E. H. F. (1999). Object relocation: A program for setting up, running, and analyzing experiments on memory for object locations. *Behavior Research Methods, Instruments, & Computers, 31*(3), 423–428. https://doi.org/10.3758/bf03200721.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352–358. https://doi.org/10.1037/h0043688.

Kozhevnikov, M., & Thornton, R. (2006). Real-time data display, spatial visualization ability, and learning force and motion concepts. *Journal of Science Education and Technology, 15*(1), 111–132. https://doi.org/10.1007/s10956-006-0361-0.

Kozhevnikov, M., Schloerb, D. W., Blazhenkova, O., Koo, S., Karimbux, N., Donoff, R. B., et al. (2013). Egocentric versus allocentric spatial ability in dentistry and haptic virtual reality training. *Applied Cognitive Psychology, 27*(3), 373–383. https://doi.org/10.1002/acp.2915.

Lavric, A., Rippon, G., & Gray, J. R. (2003). Threat-evoked anxiety disrupts spatial working memory performance: An attentional account. *Cognitive Therapy and Research, 27*(5), 489–504. https://doi.org/10.1023/a:1026300619569.

Lejbak, L., Crossley, M., & Vrbancic, M. (2011). A male advantage for spatial and object but not verbal working memory using the n-back task. *Brain and Cognition, 76*(1), 191–196. https://doi.org/10.1016/j.bandc.2010.12.002.

Li, S.-C., Schmiedek, F., Huxhold, O., Röcke, C., Smith, J., & Lindenberger, U. (2008). Working memory plasticity in old age: Practice gain, transfer, and maintenance. *Psychology and Aging, 23*(4), 731–742. https://doi.org/10.1037/a0014343.

Loftus, J. J., Jacobsen, M., & Wilson, T. D. (2017). Learning and assessment with images: A view of cognitive load through the lens of cerebral blood flow. *British Journal of Educational Technology, 48*(4), 1030–1046. https://doi.org/10.1111/bjet.12474.

Lufler, R. S., Zumwalt, A. C., Romney, C. A., & Hoagland, T. M. (2012). Effect of visual–spatial ability on medical students' performance in a gross anatomy course. *Anatomical Sciences Education, 5*(1), 3–9. https://doi.org/10.1002/ase.264.

Masters, M. S. (1998). The gender difference on the Mental Rotations test is not due to performance factors. *Memory & Cognition, 26*(3), 444–448. https://doi.org/10.3758/BF03201154.

Masters, M. S., & Sanders, B. (1993). Is the gender difference in mental rotation disappearing? *Behavior Genetics, 23*(4), 337–341. https://doi.org/10.1007/BF01067434.

Mayer, R. E., & Sims, V. K. (1994). For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. *Journal of Educational Psychology, 86*(3), 389–401. https://doi.org/10.1037/0022-0663.86.3.389.

McEvoy, L. K., Smith, M. E., & Gevins, A. (1998). Dynamic cortical networks of verbal and spatial working memory: Effects of memory load and task practice. *Cerebral Cortex, 8*(7), 563–574. https://doi.org/10.1093/cercor/8.7.563.

McGlone, M. S., & Aronson, J. (2006). Stereotype threat, identity salience, and spatial reasoning. *Journal of Applied Developmental Psychology, 27*(5), 486–493. https://doi.org/10.1016/j.appdev.2006.06.003.

Miller, D. I., & Halpern, D. F. (2013). Can spatial training improve long-term outcomes for gifted STEM undergraduates? *Learning and Individual Differences, 26*, 141–152. https://doi.org/10.1016/j.lindif.2012.03.012.

Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27*(3), 272–277.

Minear, M., Brasher, F., Guerrero, C. B., Brasher, M., Moore, A., & Sukeena, J. (2016). A simultaneous examination of two forms of working memory training: Evidence for near transfer only. *Memory & Cognition, 44*(7), 1014–1037. https://doi.org/10.3758/s13421-016-0616-9.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General, 130*(4), 621–640. https://doi.org/10.1037//0096-3445.130.4.621.

Moè, A., Jansen, P., & Pietsch, S. (2018). Childhood preference for spatial toys. Gender differences and relationships with mental rotation in STEM and non-STEM students. *Learning and Individual Differences, 68*, 108–115. https://doi.org/10.1016/j.lindif.2018.10.003.

Nairne, J. S., VanArsdall, J. E., Pandeirada, J. N. S., & Blunt, J. R. (2012). Adaptive memory: Enhanced location memory after survival processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(2), 495–501. https://doi.org/10.1037/a0025728.

Nystrom, L. E., Braver, T. S., Sabb, F. W., Delgado, M. R., Noll, D. C., & Cohen, J. D. (2000). Working memory for letters, shapes, and locations: FMRI evidence against stimulus-based regional organization in human prefrontal cortex. *NeuroImage, 11*(5), 424–446. https://doi.org/10.1006/nimg.2000.0572.

Örün, Ö., & Akbulut, Y. (2019). Effect of multitasking, physical environment and electroencephalography use on cognitive load and retention. *Computers in Human Behavior, 92*, 216–229. https://doi.org/10.1016/j.chb.2018.11.027.

Peters, M., & Battista, C. (2008). Applications of mental rotation figures of the Shepard and Metzler type and description of a mental rotation stimulus library. *Brain and Cognition, 66*(3), 260–264. https://doi.org/10.1016/j.bandc.2007.09.003.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*(1), 39–58. https://doi.org/10.1006/brcg.1995.1032.

Phillips, W. A., & Baddeley, A. (1971). Reaction time and short-term visual memory. *Psychonomic Science, 22*(2), 73–74. https://doi.org/10.3758/BF03332500.

Pilegard, C., & Mayer, R. E. (2018). Game over for Tetris as a platform for cognitive skill training. *Contemporary Educational Psychology, 54*, 29–41. https://doi.org/10.1016/j.cedpsych.2018.04.003.

Postma, A., Jager, G., Kessels, R. P. C., Koppeschaar, H. P. F., & van Honk, J. (2004). Sex differences for selective forms of spatial memory. *Brain and Cognition, 54*(1), 24–34. https://doi.org/10.1016/S0278-2626(03)00238-0.

Pouw, W., Mavilidi, M.-F., van Gog, T., & Paas, F. (2016). Gesturing during mental problem solving reduces eye movements, especially for individuals with lower visual working memory capacity. *Cognitive Processing, 17*(3), 269–277. https://doi.org/10.1007/s10339-016-0757-6.

Resnick, I., & Shipley, T. F. (2013). Breaking new ground in the mind: An initial study of mental brittle transformation and mental rigid rotation in science experts. *Cognitive Processing, 14*(2), 143–152. https://doi.org/10.1007/s10339-013-0548-2.

Richardson, J. T. E. (2003). Howard Andrew Knox and the origins of performance testing on Ellis Island, 1912-1916. *History of Psychology, 6*(2), 143–170. https://doi.org/10.1037/1093-4510.6.2.143.

Roach, V. A., Fraser, G. M., Kryklywy, J. H., Mitchell, D. G. V., & Wilson, T. D. (2019). Guiding low spatial ability individuals through visual cueing: The dual importance of where and when to look. *Anatomical Sciences Education, 12*(1), 32–42. https://doi.org/10.1002/ase.1783.

Rudkin, S. J., Pearson, D. G., & Logie, R. H. (2007). Executive processes in visual and spatial working memory tasks. *The Quarterly Journal of Experimental Psychology, 60*(1), 79–100. https://doi.org/10.1080/17470210600587976.

Ruggiero, G., Sergi, I., & Iachini, T. (2008). Gender differences in remembering and inferring spatial distances. *Memory, 16*(8), 821–835. https://doi.org/10.1080/09658210802307695.

Sanchez, C. A. (2012). Enhancing visuospatial performance through video game training to increase learning in visuospatial science domains. *Psychonomic Bulletin & Review, 19*(1), 58–65. https://doi.org/10.3758/s13423-011-0177-7.

Saryazdi, R., Bannon, J., Rodrigues, A., Klammer, C., & Chambers, C. G. (2018). Picture perfect: A stimulus set of 225 pairs of matched clipart and photographic images normed by mechanical Turk and laboratory participants. *Behavior Research Methods, 50*(6), 2498–2510. https://doi.org/10.3758/s13428-018-1028-5.

Schmiedek, F., Hildebrandt, A., Lövdén, M., Wilhelm, O., & Lindenberger, U. (2009). Complex span versus updating tasks of working memory: The gap is not that deep. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(4), 1089–1096. https://doi.org/10.1037/a0015730.

Schwaighofer, M., Bühner, M., & Fischer, F. (2016). Executive functions as moderators of the worked example effect: When shifting is more important than working memory capacity. *Journal of Educational Psychology, 108*(7), 982–1000. https://doi.org/10.1037/edu0000115.

Schwarb, H., Nail, J., & Schumacher, E. H. (2016). Working memory training improves visual short-term memory capacity. *Psychological Research, 80*(1), 128–148. https://doi.org/10.1007/s00426-015-0648-y.

Seufert, T., Schütze, M., & Brünken, R. (2009). Memory characteristics and modality in multimedia learning: An aptitude-treatment-interaction study. *Learning and Instruction, 19*(1), 28–42. https://doi.org/10.1016/j.learninstruc.2008.01.002.

Shackman, A. J., Sarinopoulos, I., Maxwell, J. S., Pizzagalli, D. A., Lavric, A., & Davidson, R. J. (2006). Anxiety selectively disrupts visuospatial working memory. *Emotion, 6*(1), 40–61. https://doi.org/10.1037/1528-3542.6.1.40.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General, 125*(1), 4–27. https://doi.org/10.1037/0096-3445.125.1.4.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701–703. https://doi.org/10.2307/1731476.

Silverman, I., Choi, J., & Peters, M. (2007). The hunter-gatherer theory of sex differences in spatial abilities: Data from 40 countries. *Archives of Sexual Behavior, 36*(2), 261–268. https://doi.org/10.1007/s10508-006-9168-6.

Smirni, P., Villardita, C., & Zappalà, G. (1983). Influence of different paths on spatial memory performance in the Block-Tapping Test. *Journal of Clinical Neuropsychology, 5*(4), 355–359. https://doi.org/10.1080/01688638308401184.

So, W.-C., Shum, P. L.-C., & Wong, M. K.-Y. (2015). Gesture is more effective than spatial language in encoding spatial information. *The Quarterly Journal of Experimental Psychology, 68*(12), 2384–2401. https://doi.org/10.1080/17470218.2015.1015431.

Stephenson, C. L., & Halpern, D. F. (2013). Improved matrix reasoning is limited to training on tasks with a visuospatial component. *Intelligence, 41*(5), 341–357. https://doi.org/10.1016/j.intell.2013.05.006.

Stieff, M., & Uttal, D. H. (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review, 27*(4), 607–615. https://doi.org/10.1007/s10648-015-9304-8.

Stransky, D., Wilcox, L. M., & Dubrowski, A. (2010). Mental rotation: Cross-task training and generalization. *Journal of Experimental Psychology: Applied, 16*(4), 349–360. https://doi.org/10.1037/a0021702.

Stull, A. T., & Hegarty, M. (2016). Model manipulation and learning: Fostering representational competence with virtual and concrete models. *Journal of Educational Psychology, 108*(4), 509–527. https://doi.org/10.1037/edu0000077.

Stull, A. T., Hegarty, M., & Mayer, R. E. (2009). Getting a handle on learning anatomy with interactive three-dimensional graphics. *Journal of Educational Psychology, 101*(4), 803–816. https://doi.org/10.1037/a0016849.

Stull, A. T., Fiorella, L., Gainer, M. J., & Mayer, R. E. (2018a). Using transparent whiteboards to boost learning from online STEM lectures. *Computers & Education, 120*, 146–159. https://doi.org/10.1016/j.compedu.2018.02.005.

Stull, A. T., Fiorella, L., & Mayer, R. E. (2018b). An eye-tracking analysis of instructor presence in video lectures. *Computers in Human Behavior, 88*, 263–272. https://doi.org/10.1016/j.chb.2018.07.019.

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*(3), 498–505. https://doi.org/10.3758/bf03192720.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*(2), 599–604. https://doi.org/10.2466/pms.1978.47.2.599.

Voyer, D., & Hou, J. (2006). Type of items and the magnitude of gender differences on the Mental Rotations Test. *Canadian Journal of Experimental Psychology, 60*(2), 91–100. https://doi.org/10.1037/cjep2006010.

Vuoksimaa, E., Kaprio, J., Kremen, W. S., Hokkanen, L., Viken, R. J., Tuulio-Henriksson, A., et al. (2010). Having a male co-twin masculinizes mental rotation performance in females. *Psychological Science, 21*(8), 1069–1071. https://doi.org/10.1177/0956797610376075.

Wanzel, K. R., Hamstra, S. J., Anastakis, D. J., Matsumoto, E. D., & Cusimano, M. D. (2002). Effect of visual-spatial ability on learning of spatially-complex surgical skills. *The Lancet, 359*(9302), 230–231. https://doi.org/10.1016/S0140-6736(02)07441-X.

Wilson, L., Scott, J. H., & Power, K. G. (1987). Developmental differences in the span of visual memory for pattern. *British Journal of Developmental Psychology, 5*(3), 249–255. https://doi.org/10.1111/j.2044-835X.1987.tb01060.x.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review, 15*(4), 763–771. https://doi.org/10.3758/PBR.15.4.763.

Wu, Y. C., & Coulson, S. (2014). Co-speech iconic gestures and visuo-spatial working memory. *Acta Psychologica, 153*, 39–50. https://doi.org/10.1016/j.actpsy.2014.09.002.

Wu, S. P. W., & Rau, M. A. (2018). Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations. *Learning and Instruction, 55*, 93–104. https://doi.org/10.1016/j.learninstruc.2017.09.010.