

Chapter 5

Visuospatial Cognition



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Abstract In this chapter, we present theory and research on early- and later-developing visuospatial cognition into adulthood and its importance to mathematical cognitive development. We describe the development of dorsal and ventral visual pathways associated with the visuospatial functions of spatial awareness and pattern processing. Research using cognitive neuroscience techniques, including functional Magnetic Resonance Imaging (fMRI), Electroencephalography (EEG), and Transcranial Magnetic Stimulation (TMS), is presented on the following topics relevant to visuospatial cognition and its development: visual attention and search, visual perception and judgment, geometry, visual imagery and mental rotation, and visuospatial working memory. We conclude that the parietal lobe plays an important role in general visuospatial cognition and that the right hemisphere is dominant for certain visuospatial skills. Other brain areas related to visuospatial cognition include the superior frontal gyrus/sulcus, anterior insular cortex, temporal-occipital cortex, dorsolateral prefrontal cortex, precentral gyrus, and left hemisphere dorsal anterior cingulate cortex.

Transport yourself back to school, perhaps back to a geometry class. Imagine posters of different shapes that may have been up on the walls. Which ones draw your attention? Does your attention shift from one shape to another? Perhaps you detect patterns within a more complex geometric design. Are there any 3-dimensional (3D) representations of shapes within the room? If so, pick one, close your eyes, and imagine you're holding it in your hand. Now turn it over and look at all sides of the shape. Put that shape down, and with your eyes still closed, think about what other images you remember viewing just a moment ago.

If you performed any of the tasks described just now, you made use of an array of visuospatial skills. *Visuospatial cognition* encompasses a variety of skills, including searching for and locating objects, shifting spatial attention, holding items in your visual memory, performing mental rotations, and detecting patterns, among others.

Neural Basis of Visuospatial Cognition

Research conducted with adults has described two major cortical streams related to visuospatial cognition: the dorsal visual pathway and the ventral visual pathway (e.g., Goodale & Milner, 1992; Mishkin & Ungerleider, 1982). Anatomically, both pathways begin at the retina where visual information is first received, and proceed to the primary visual cortex, referred to as V1, in the occipital lobe. From there, however, the pathways diverge, with the *dorsal visual pathway* projecting forward to the temporal lobe and then to the inferior parietal lobe, and the *ventral visual pathway* proceeding downward to the inferior temporal lobe. Each pathway has been associated with specific visuospatial functions. The dorsal stream, commonly referred to as the *where* or *how* stream, involves tasks primarily related to spatial awareness and action planning (Chinello, Cattani, Bonfiglioli, Dehaene, & Piazza, 2013; Stiles, Paul, & Ark, 2008). The ventral visual pathway, known as the *what* stream, is used in tasks involving part-whole or global-local visual pattern processing (Stiles et al., 2008). Figure 5.1 depicts each pathway from the left hemisphere lateral view.

Stiles et al. (2008) reviewed the literature on the development of brain networks and functions related to visuospatial processing. While many visuospatial skills are established early in life, many of those skills show protracted development. For example, they describe studies showing that children as young as 5 can perform mental rotations; however, they also noted that their speed and accuracy continues

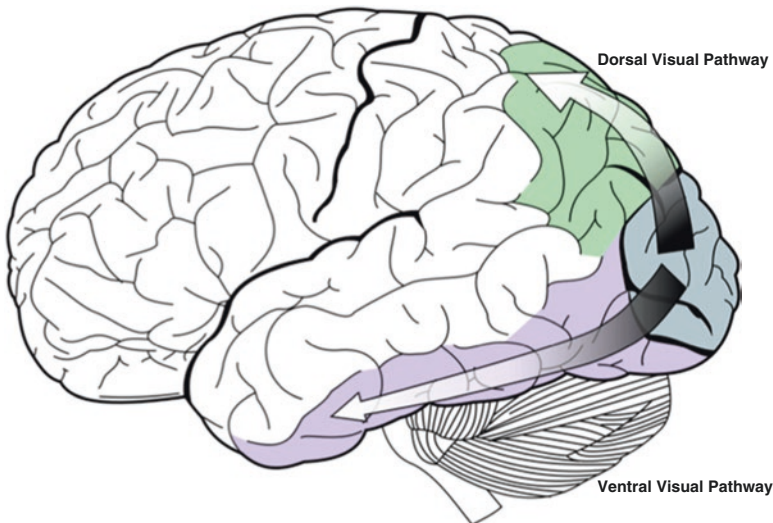


Fig. 5.1 The left hemisphere (lateral view) indicating the dorsal and ventral visual pathways. Photograph by Selket (From File: Gray728.svg) [GFDL (<http://www.gnu.org/copyleft/fdl.html>), CC-BY-SA-3.0 (<http://creativecommons.org/licenses/by-sa/3.0/>) or CC BY-SA 2.5-2.0-1.0 (<http://creativecommons.org/licenses/by-sa/2.5-2.0-1.0/>)], via Wikimedia Commons

to develop and improve through adolescence. They drew similar conclusions from their review of ventral stream skills, such as pattern processing. Also common to their findings is evidence of connectivity between regions of the brain. For example, with respect to spatial location, a network of neural systems emerges as early as the first year of life, involving areas in both the frontal and parietal lobes.

Some studies have sought to specifically explore the nature of developmental changes within the two major visuospatial streams. As described previously, each stream is associated with functions that answer a general question: the *where* versus the *what*. Therefore, you might expect that there would be certain correlations between those associated functions. By that same logic, you may also expect there to be little correlations among functions between the two streams. Chinello et al. (2013) investigated these issues by administering a series of tasks to both kindergarten-aged children and adults to measure six specific abilities: numerical acuity, finger gnosis (i.e., finger recognition or localization), visuospatial memory, grasping precision, face recognition, and object recognition. As hypothesized, Chinello and colleagues found that, for children, there are significant correlations among tasks falling within a particular functional domain (dorsal or ventral), but little correlation on tasks between domains. However, adults showed lower correlations overall, whether within or between domains, suggesting that certain visuospatial skills that are more interrelated during early childhood may become more specialized during adulthood. Overall, Chinello and colleagues concluded that functions between the two major visuospatial streams are unrelated and follow their own specific developmental trajectories (for a different perspective, see Pisella et al., 2013). More specifically, they found that the development of finger gnosis, spatial abilities, and nonsymbolic numerical abilities were correlated independently of chronological age. Chinello and colleagues attributed the source of this correlation to finger counting, speculating that finger gnosis would improve with finger counting by increasing individual finger representations and their relative position in space and that finger counting would improve spatial abilities by tracking multiple items in parallel with the corresponding mental representation of numerical quantities. Indeed, in children attending kindergarten, strategies for solving addition problems, including finger counting, were significantly correlated with spatial, but not verbal subtests of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI; Geary & Burlingham-Dubree, 1989).

Thus, while the various structures and networks of the brain related to visuospatial cognition are well identified, the developmental pathways of these structures, along with connectivity between them, are not clearly understood. Therefore, in this chapter, we review some of the major functions that fall within the realm of visuospatial cognition, identify the major areas of the brain associated with those functions, and describe what is known about how those functions change with development.

Before proceeding, however, it is important to place the role of visuospatial cognition within the context of mathematical cognitive development, the focus of this text in general. Intuitively, it perhaps seems obvious that visuospatial skills would play a major role in mathematical cognitive development. In Chap. 4, results on the

mental addition and subtraction of fractions were presented from Schmithorst and Brown (2004) that indicated a bilateral inferior ventral occipitotemporal component of the ventral visual pathway, including the inferior temporal gyrus and fusiform gyrus. These areas comprise the *visual system* of the triple-code model (see Chap. 1), which may have been used to recognize numerators in comparison to denominators and spatially manipulate the fractions in Arabic format to calculate solutions that could not be retrieved from memory. We also found a component of medial-superior occipital gyrus activation and suggested that neural correlates of the *visual system* might extend beyond the ventral visual pathway into other secondary visual areas.

Wai, Lubinski, and Benbow (2009) cite longitudinal studies showing correlations between spatial ability and later Science Technology Engineering and Mathematics (STEM) related degrees and careers. Thus, spatial ability could have important implications for guiding coursework, career pursuits, and appropriate interventions. Wai et al. (2009) conducted a study involving a sample of 400,000 high school students, based on available data on spatial ability, along with degree and career data from an 11-year follow-up and found that spatial ability was indeed a reliable predictor of advanced STEM degrees, as well as occupational outcomes. Figure 5.2 shows example items from their measures of spatial ability. Importantly, their sample was not solely comprised of academically high-achieving students, suggesting that these implications are applicable to the general population. Given findings such as these, the importance of visuospatial ability to mathematical cognitive development cannot be underestimated. Keeping this in mind, the following sections will review specific functions within the scope of visuospatial cognition.

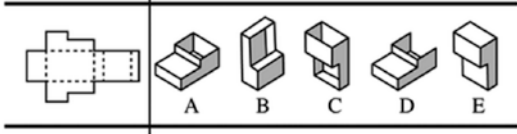
Visual Attention and Search

Let's return to our imaginary geometry class. As you look around, are there shapes that seem to draw your attention involuntarily? In contrast, what if we asked you to find and look at a specific one—a circle, a parallelogram, or a cone? What if we asked you to look around and find examples of specific shapes hidden within objects or patterns in the room? Or what if we asked you to note all of the spherical objects you could see—where are they located in relation to each other? These are examples of activities that involve visual attention and visual search.

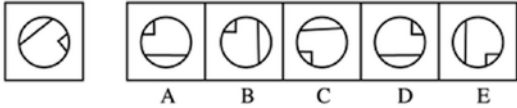
One important concept to remember about these functions is that they are not uniform in nature. There is no single definition of attention, but several types. For example, consider if you found yourself in a room where there was a fluorescent light flickering above. In that case, your attention would shift involuntarily to the light as a result of a stimulus. However, if we ask you to search for something specific, as we did above when mentioning a circle, parallelogram, or cone, your attention became goal-oriented in nature. Similarly, searching for one particular shape in a room means you have to match criteria in a specific, localized fashion; but asking you to locate all of the representations of that shape requires a more globalized view.

Fig. 5.2 Example items from four tasks measuring spatial ability: 3D spatial visualization, 2D spatial visualization, mechanical reasoning, and abstract reasoning. Source: 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>

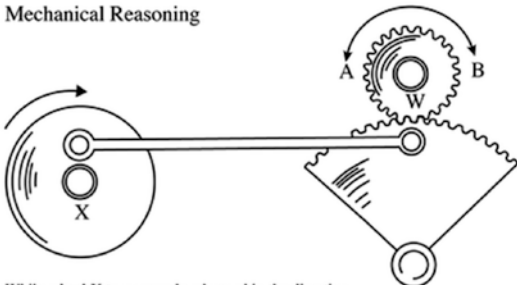
Three Dimensional Spatial Visualization



Two Dimensional Spatial Visualization



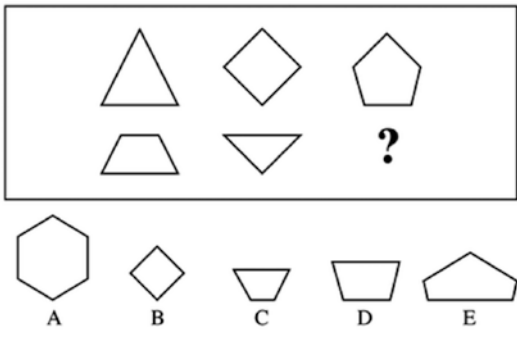
Mechanical Reasoning



While wheel X turns round and round in the direction shown, wheel W turns

- A. in direction A.
- B. in direction B.
- C. first in one direction and then in the other.

Abstract Reasoning



The dorsal stream is used in tasks involving spatial attention and orientation, spatial localization, and mental rotation. Briefly, research on *spatial attention*, and more specifically, *spatial orientation*, has shown that a posterior parietal network is involved in disengaging attention from one location, shifting it to a different location, and inhibiting a return of attention to the original location, which is thought to be an evolutionarily important phenomenon (e.g., Posner, 1980; Posner & Petersen, 1990). Like numerosity and ordinality, these abilities appear to be present very early in life, but show improvement between 2 and 4 months, and are mostly functional by 6 months (e.g., Butcher, Kalverboer, & Geuze, 1999; Clohessy, Posner, Rothbart, & Vecera, 1991; Hood, 1993; Simion, Valenza, Umiltà, & Dalla Barba, 1995; Valenza, Simion, & Umiltà, 1994). With age and experience, visual attention skills become more right lateralized. For example, Smith and Chatterjee (2008) reported that 12- to 14-year-olds with slower responses in both local and global attention tasks displayed more bilateral activation than better performing peers, who displayed a greater tendency towards right hemisphere activation. In adults, the right hemisphere, particularly the superior parietal cortex, is the dominant locale for visuospatial skills. In their study, Everts et al. (2009) administered visual search tasks while participants were in an MRI scanner. Participants also completed assessments measuring their visuospatial ability. Results showed that visual search was associated with bilateral frontal, superior temporal, and occipital regions, indicating interconnectivity of visuospatial networks. Additionally, Everts and colleagues found that lateralization of activity within the right hemisphere, particularly in the frontal and parietal regions, increased not only with age, but also with increased performance on visuospatial assessments. These results are consistent with Chinello et al.'s (2013) findings suggesting that age and greater efficiency contribute to increased specialization in the brain related to visuospatial function.

Visual Perception and Judgment

Visual perception is a broad term that encompasses several possible functions. Back in our geometry class, imagine if we were to show you a series of geometric shapes on note cards. In addition to different shapes being present, imagine too that there are differences in shading, the thickness of lines, the orientation of the shapes in relation to each other, the number of certain shapes appearing in a row, and so on. Whenever you notice those different aspects, you are activating a particular function within the realm of visual perception.

In terms of the areas of the brain involved in various visuospatial perception tasks, we see many commonalities with those already described in the dorsal and ventral streams, as well as in the areas related to visual attention and search. Ebisch et al. (2012) conducted a study investigating the nature of fluid intelligence by having participants perform four tasks while undergoing fMRI. Tasks specific to visuospatial perception included *induction*, for which participants must determine common characteristics among stimuli; *visualization*, for which participants must

manipulate visual images; and *spatial relationship*, for which participants are required to identify spatial patterns or orientations among objects. Brain areas that showed common activation across different tasks included the bilateral superior frontal gyrus/sulcus, inferior parietal lobe, intraparietal sulcus (IPS), posterior parietal cortex, superior parietal cortex, anterior insular cortex, temporal-occipital cortex, dorsolateral prefrontal cortex, precentral gyrus, and left hemisphere dorsal anterior cingulate cortex (ACC). These results indicate that visual perception involves a distributed frontoparietal network. For the visualization task, there was significant activation of the bilateral inferior parietal lobe, as well as the right hemisphere dorsal ACC. These results are consistent with other findings stressing not only the importance of the parietal lobe in general visuospatial cognition, but also the dominance of the right hemisphere with respect to certain visuospatial functions. Additionally, Ebisch and colleagues found that participants who scored higher on fluid intelligence assessments showed greater functional connectivity between these different brain areas, once again suggesting that specialization of the brain occurs not only with age, but also with increased skill and efficiency.

Other studies have shown similar results, and have sought to expand on them by including developmental data as well. Eslinger et al. (2009) conducted an fMRI study in which participants aged 8–19 completed *relational reasoning* tasks. Specifically, participants had to identify a correct response in order to complete a series of images based on dimensions of color and shape. They found a network of related structures involved in these types of tasks including the superior parietal cortex, the dorsolateral prefrontal cortex, the superior premotor/supplementary motor region, and the occipital-temporal cortex, with the greatest level of activation in the right and left superior parietal cortices. In this primary area, Eslinger and colleagues found increased activation with age. They noted a contrast in the bilateral nature of activation in their study compared to lateral specialization in other studies, although this could be accounted for by the broad nature of the visuospatial tasks used. Interestingly, they found that certain areas showed decreased activation with age, notably the prefrontal-frontal cortex and the cingulate. As previously discussed, with age, children likely become more efficient in performing visuospatial tasks, which translates into a decreased need for executive function, attention, working memory, and so on, functions associated with the decreased brain activation areas mentioned above (i.e., the Default Mode Network [DMN]).

Regarding lateralization, Fink et al. (2000) conducted an fMRI study in which adult male participants had to judge if lines were correctly bisected. Scan results showed distinct and significant activation of the right hemisphere superior parietal cortex as well as the right inferior parietal cortex. Other studies have attempted to investigate this apparent hemispheric specialization and its place within the functional connectivity network that seems to exist in visuospatial skills. Sack et al. (2007) used transcranial magnetic stimulation (TMS; see Chap. 2 for a description) as a way to disrupt neural activity within the parietal lobe, and then measure effects on behavioral performance, as well as neural activity in both stimulated and unstimulated areas of the brain through fMRI scans. The adult participants in the study were asked to identify either angle-based or color-based targets on a series of clock

images, both in a control trial and in a trial where TMS was applied. Results demonstrated that, consistent with past research, the parietal and frontal lobes showed activation during both visual tasks. As predicted, right parietal TMS resulted in decreased behavioral performance as well as decreased activity in the stimulated area. However, decreased activation was also seen in the right postcentral gyrus and the middle frontal gyrus. These extended decreased activation areas were not observed when left parietal TMS was applied. These results further support the importance of the right parietal lobe in visuospatial tasks, and also demonstrate the functionally connective nature of the frontoparietal network with respect to visuospatial cognition.

Building on this study, de Graaf, Roebroek, Goebel, and Sack (2010) conducted research to further investigate the specific patterns of this functional connectivity. They had adult participants perform the same tasks described above used by Sack et al. (2007), and then used fMRI to measure brain activation. Furthermore, de Graaf and colleagues employed a connectivity analysis technique known as *Granger Causality Mapping (GCM)* to investigate more closely the interactions within the established visuospatial network. Their results indicated a strong connectivity between the posterior parietal cortex and the middle frontal gyrus, which is consistent with past findings. They also identified directional aspects of this network, displaying a flow of information from the frontal to the parietal lobe. While the flow was mainly from the middle frontal gyrus to the posterior parietal cortex, other frontal regions were indicated as well, such as the insula. Other areas possibly involved in this network include the superior frontal sulcus, postcentral gyrus, and occipital cortex.

Many of the studies of visual perception described to this point indicate a certain degree of specialization that occurs in the brain with age, experience, or efficiency. Another possible mediator of specialization that is of particular interest in this text is task-specific—namely, tasks related to mathematical function. As previously noted, associations have been established between visuospatial cognition and mathematical skills. Some mathematical tasks relate directly to visuospatial cognition, such as those involving geometry (see Fig. 5.3). Izard, Pica, Dehaene, Hinchey, and Spelke (2011) sought to understand what sort of inherent ability we might have for geometric tasks as they relate to spatial perception. They conducted a study in which participants had to identify figures in a series of images that were different in some way; those differences could be related to one of a few geometric features, such as angle, size, or sense. By comparing results between children, adults, and an Amazonian tribe with no formal geometry education, Izard and colleagues found that certain geometric intuitions do indeed appear to be universal. However, developmental differences were noted with respect to certain tasks. In task trials involving stimuli related to length and angle, children performed well. However, in tasks requiring spatial sense, children were outperformed by adults, indicating a protracted development for certain types of visuospatial perception.

Other studies have added to the research on specific math-related visuospatial skills by investigating activity within specific brain circuits. Mangina et al. (2009) note that task stimuli involving size and dimension correlate more with mathematical

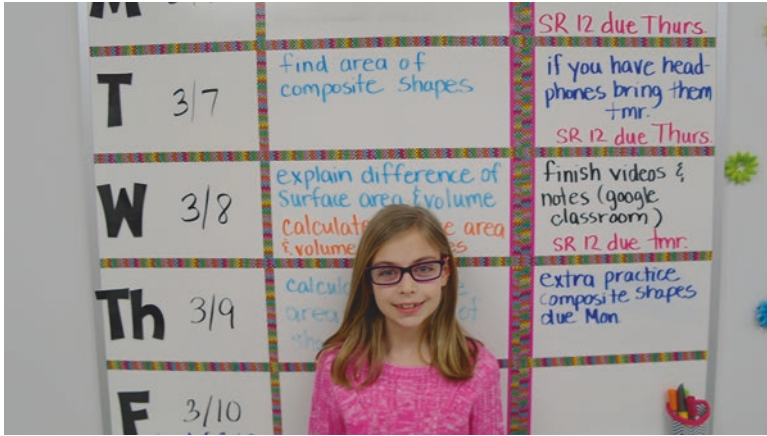


Fig. 5.3 Some mathematical tasks relate directly to visuospatial cognition, such as those involving geometry, and are incorporated into mathematics curricula across grade levels

skills, and tasks involving orientation relate more to reading skills. In an effort to see if these differences are reflected in brain activity, they administered different perceptual tasks to participants that related specifically to direction, spatial orientation, size, or dimension. The adult participants were required to identify similar stimuli according to one of the factors listed above while fMRI scans were conducted to measure brain activity. As with previous visuospatial studies, Mangina and colleagues identified overall activity within a distributed network that included the prefrontal cortex as well as the occipitotemporal and parietal regions. However, tasks related more to mathematical skills (i.e., those involving size and dimension) revealed activation in the bilateral posterior parietal, premotor, and prefrontal regions. These findings contrast with reading-related skills, which showed activation in the occipitotemporal and sensorimotor cortices.

Overall then, while studies of visual perception cover a broad array of topics, they establish clear evidence of a frontoparietal network and a high level of connectivity between these brain regions, indicating that disruption to activity in one area can affect activity in another. The available data suggest that both lateral and focal specialization within this network is mediated by contributing factors such as age, experience, and task specificity.

Visual Imagery and Mental Rotation

So far we've discussed attention to and perception of actual stimuli in our environment. But, in addition to what is directly perceivable, visuospatial cognition also encompasses our ability to picture objects and spatial relationships in our minds.

For instance, imagine a map from your home to place of work. Perhaps consider a map that includes not only routes and direction, but also one that includes actual images as well, as if it was a picture from a satellite. How many landmarks, buildings, natural objects, and so on can you picture from that route and with how much detail? What color are the buildings? How big are the trees? Where are structures located in relation to one another? As you drive along your route, how does your perspective of a building change as you drive towards it, past it, and then away from it? What you pictured above involves not only visual imagery, but manipulation of that imagery as well.

It is first important to realize the different types of visual imagery. Let us return for a moment to the beginning of this chapter when we discussed two primary cortical streams involved in visuospatial cognition. Remember how we distinguished between the dorsal stream, the *where* pathway concerned with spatial awareness, and the ventral stream, the *what* pathway concerned with object recognition? The available research on the basics of visual imagery indicates two basic types of imagery that seem to fit within these two cortical streams.

One type is known as *spatial imagery*, and refers to a person considering the spatial relationship between objects and how they might exist or move in relation to each other. So, when we asked you to imagine the placement of structures along your route, you were making use of spatial imagery. The other type is known as *object imagery*, and as its name implies, it refers to a person actually picturing an object in his or her mind (Kozhevnikov & Blazhenkova, 2013). When we asked you to imagine the specific buildings and landmarks, you were making use of object imagery. Research supports both functional and anatomical differences between these two types of imagery, with processes related to spatial imagery being contained more within the occipitoparietal dorsal pathway and object imagery being contained more within the occipitotemporal ventral pathway (Kozhevnikov & Blazhenkova, 2013).

Much of the cognitive neuroscience research on visual imagery has investigated spatial imagery. Kozhevnikov and Blazhenkova (2013) refer to past research that indicates that structures within the dorsal pathway seem to show less neural activity in people that perform better on spatial reasoning tasks. This inverse relationship between high performance on tasks and lower activity in those task-related areas of the brain is known as *neural efficiency* (Kozhevnikov & Blazhenkova, 2013), the idea that a person who is skilled in these sorts of tasks is able to make better and more efficient use of brain resources during task performance. For example, Kozhevnikov and Blazhenkova describe fMRI studies indicating that participants who are more skilled in object imagery tasks typically show less activation in the occipital complex when asked to study and visualize line drawings of common objects than participants who are more skilled in spatial imagery tasks.

There are other differences between the two imagery types. With regards to development, spatial ability seems to increase and peak during adolescence, followed by a decline into adulthood (Kozhevnikov & Blazhenkova, 2013). Object ability, however, seems to increase continually with age. These fundamental differences between the two imagery types may have educational implications as well,

especially considering the fact that the increased use of spatial reasoning typically leads to increased success in mathematical problem solving, as noted in Kozhevnikov and Blazhenkova (2013), as well in other studies mentioned previously in this chapter. There seem to be sex differences involved in visual imagery as well. Perhaps the area of visual imagery for which this is most evident is *mental rotation*, which involves a person's ability to imagine how an object would look in a different orientation. If you think back to when we asked you how a building would look depending on your angle to it while driving, you may have employed mental rotation during that exercise. As it relates to the two distinct types of imagery, mental rotation falls under the umbrella of spatial imagery. Going back to sex differences, Kozhevnikov and Blazhenkova (2013) note that available research points to females being more skilled in tasks of object imagery, and males being more skilled in tasks of spatial imagery, such as mental rotation.

Roberts and Bell (2000) used electroencephalography (EEG) to investigate differences in brain activity with regard to both sex and age during mental rotation tasks. They noted that while previous research had indicated that men tend to display greater right parietal activation than women during mental rotation tasks, little research had been done to include the factor of development. To that end, they conducted a study with a group of 8-year-old children and a group of college students, both male and female. Participants were shown a figure of a gingerbread man. Two versions of that figure were then presented, each rotated at a different angle from the original. Participants were asked to identify which of the two choices matched the original, which would involve mental rotation of the figure to its original position. In terms of developmental differences, adult participants displayed more activation in all brain areas measured than children, with the exception of the lateral frontal area. Meanwhile, the comparison of men and women showed that men displayed more activation in the posterior temporal, parietal, and occipital regions, consistent with previous research. Interestingly, these activation differences were not seen between male and female children, suggesting a developmental factor in mental rotation with regards to sex differences. One result that was somewhat inconsistent with past research was that men displayed greater parietal activation in the left hemisphere as opposed to the right. However, the researchers suggested that this result may be in line with a male advantage for mental rotation tasks, as previous research has indicated that simple rotation tasks typically elicit greater left hemisphere activation than complex tasks. In this case, if the task was indeed easier for the male participants, then greater left hemisphere activation seems plausible.

Other studies have further investigated these apparent sex differences. Neubauer, Bergner, and Schatz (2010) noted some of the inconsistencies in the stability of mental rotation performance, citing studies that show performance can be enhanced through practice and training. Additionally, the advantage that males have on these tasks seems to disappear when the task is presented in 3D, rather than 2-dimensionally (2D). They conducted an EEG study in which they presented a mental rotation task involving 3D cubes to adolescents. Different trials were conducted involving both 2D presentation (on a screen) and 3D presentation (using 3D glasses). Pre- and post-tests were also completed after a training specifically designed for mental rotation

tasks. Neubauer and colleagues found that sex differences in terms of task performance only held for the 2D version of the task. Additionally, females were able to increase their performance to a greater degree following the training. Consistent with previous research, activity was generally right lateralized in parietal regions for both sexes. One interesting note was that increased neural efficiency after training was seen in males overall, but in females neural efficiency only increased for the 3D task, rather than the 2D task. These findings suggest that mental rotation task performance is malleable, indicating that activation and performance can depend on factors such as experience and the nature of the stimuli.

Development seems to be an important factor in tasks of mental rotation. A number of studies have investigated how children perform on these tasks, and what patterns of brain activation they display. Heil and Jansen-Osmann (2007) cite previous research indicating that although adults show increased right parietal activity during mental rotation, children display greater left hemisphere activation. To validate this finding, they conducted an EEG study with a group of 7- and 8-year-old children involving mental rotation of alphabetical letters. Consistent with the pattern seen in the research on spatial reasoning in general, the most pronounced activation was seen in the parietal lobe. Additionally, results showed increased activity in the left hemisphere. The researchers speculated that this hemispheric difference between children and adults stems from how the two groups approach the task. Children may engage in more complex part-representations of mental rotation, whereas adults may engage in a simpler whole-representation of the entire figure. These approaches could correspond to differences in areas of activation. To build upon this study, Lange, Heil, and Jansen (2010) conducted an additional EEG study with the goal of determining whether this hemispheric difference in children may be stimulus dependent. Instead of alphabetical letters, children were required to mentally rotate line drawings of animals. While activity was again displayed in the parietal region, there was no lateralization effect. This finding seems to support the results obtained by Neubauer et al. (2010), which point to a variability in mental rotation tasks based on task stimuli.

Visuospatial Working Memory

Throughout the chapter, we've presented you with a variety of imaginary tasks. Many of these tasks required you to picture shapes you are familiar with. Others required you to navigate through an imaginary space. What can you remember about those tasks right now? Are you still able to picture the shapes you found hidden in objects in your geometry class? What did they look like? Can you picture them with the same detail you did some moments ago? What about when we asked you to drive past a building—can you still remember the exact route you took in your mind?

Just now, the questions we asked caused you to make use of your visuospatial memory. Related to general visuospatial memory is *visuospatial working memory*

(*VSWM*). Working memory in general is not a concept specific to visuospatial cognition. In fact, working memory involves a few different functions such as memory, attention, and perception, and it is what allows you to hold pieces of information in your mind while you operate on that information and use it towards a goal (Scherf, Sweeney, & Luna, 2006). Therefore, *VSWM* involves such abilities as being able to picture a novel object you just observed, or being able to remember a spatial pattern of movement. Anyone who has ever played the game Simon is probably familiar with latter, in which you must remember and repeat a pattern of sequential lighted buttons.

Just as with other concepts within visuospatial cognition, there are certain areas of the brain that have been implicated for *VSWM* tasks. However, some background is required. Two important components of general working memory have repeatedly been identified in the literature: the *phonological loop*, relating to verbal information, and the *visuospatial sketchpad*, relating to visual information (Baddeley & Hitch, 1974). As Vecchi, Phillips, and Cornoldi (2001) note, there is evidence that these two components operate somewhat independently, such that increased load on one component will lead to increased significant interference on tasks requiring that same component, but not on tasks requiring the opposite component. Other theoretical views indicate that working memory performance may vary according to the type of stimuli being processed, as well as the degree of necessary active processing (Vecchi et al., 2001).

In terms of the type of information being processed, the subdivisions follow the same properties of the primary dorsal and ventral networks mentioned previously in this chapter. Remembering information related to the *where* of an object (e.g., the route that car takes to get home) activates the dorsal network. Remembering information related to the *what* of an object (e.g., the size and color of a car) activates the ventral network. However, there are also differences involving the degree of active processing. Passive storage of information requires only remembering previously learned information as it was originally presented (Vecchi et al., 2001). However, active processing involves not only remembering that information, but also being able to manipulate it. Our previous discussion of mental rotation is an example of this active processing.

Research has shown that there are observable developmental differences with respect to *VSWM* and its associated subdivisions. One basic observed outcome is that *VSWM* skills increase with age during childhood, although this increase may relate more to improvements in working memory in general (Vecchi et al., 2001). However, when looking specifically at passive versus active processing, a distinction does seem to arise. Given effective training strategies, children perform as well as adults on tasks involving passive storage, but not on tasks involving active processing. On the other end of the spectrum, older adults show a decline in their active processing ability, while their passive storage remains stable (Vecchi et al., 2001). Since these results are mostly based on *VSWM* test outcomes, one possible explanation for this is the novelty of *VSWM* tasks versus verbal working memory tasks. Pure *VSWM* information is free of context, which can lead to an increased requirement of executive processing in the frontal lobe. It could be that the decline in

VSWM skills in older adults has more to do with these brain areas than functions of VSWM specifically.

Other researchers have investigated the aforementioned increase in VSWM skills with age and attempted to explain them using the different components of general working memory. Pickering (2001) cites previous research indicating that when remembering visual information, young children tend to encode the information visually; as children age, they tend to translate that same information phonologically. For example, older children may use verbal labels more than actual visual imagery. Additionally, increasing VSWM skills may reflect an overall maturation in children's executive functioning, leading to more efficient use of both verbal- and visual-related processing. Pickering also notes that although verbal translation of information may account for some of this increase, it cannot explain it completely. Other factors may contribute, such as increased attentional capacity, processing speed, visuospatial knowledge, and memory strategies.

A number of cognitive neuroscience studies have been conducted to further investigate some of these developmental differences. Klingberg, Forssberg, and Westerberg (2002) conducted an fMRI study with participants ranging in age from 9 to 18. Participants were presented with a VSWM task in which they had to remember positions of a number of red circles within a grid. Results showed that certain areas of the brain were activated during the task for all age groups, including the prefrontal, cingulate, parietal, and occipital cortices. Additionally, a positive correlation was noted between age and activation in the superior frontal sulcus, the intraparietal and superior parietal cortices, and the left occipital cortex. These results are somewhat inconsistent with other studies of visuospatial cognition in which age usually correlated with lower frontal activity. However, VSWM tasks are somewhat unique in that they are not likely to improve with training and experience, leading to continued frontal activation. These results are consistent with other studies, however, in providing evidence of a frontoparietal network for visuospatial cognition. Klingberg and colleagues suggest that concurrent neurological developments, such as myelination within the parietal cortex and synaptic pruning, may contribute to the increased activation seen in this network with age.

Scherf et al. (2006) conducted an fMRI study with a group of children, adolescent, and adult participants aged 8–47. In this study, participants had to move their eye gaze to a spatial target based on previous presentation of a visual stimulus in that target area. As predicted, certain regions displayed activation for all three age groups, including the right dorsolateral prefrontal cortex, the right ACC, the bilateral interior insula, the right superior temporal gyrus, the right interoccipital sulcus, and the right basal ganglia. Interestingly, the parietal cortex was not included in these results. Developmentally, children displayed greater activation in the thalamus and cerebellum in comparison to adolescents. Additionally, children displayed less activation in the dorsolateral prefrontal, parietal, premotor, and cingulate cortices than adolescents or adults. Overall, these results are consistent with other findings indicating that the dorsal pathway has a more protracted developmental trajectory than the ventral pathway. While both adolescents and adults showed activation in the aforementioned areas, Scherf and colleagues noted that adult activation was

more left lateralized in regions consistent with use of the phonological loop. As mentioned previously, this may reflect a strategy of verbally recoding visual information for increased memory effectiveness.

Because of these apparent developmental differences in VSWM, other researchers have attempted to investigate the associated educational implications by exploring associations between VSWM and certain academic abilities, including mathematical performance. Dumontheil and Klingberg (2012) cited meta-analyses showing the IPS to be vital in numerical processing. As this area of the brain has been noted to be important to VSWM as well, they conducted a longitudinal study investigating the relationship between working memory ability, arithmetic performance, and brain activation in children aged 6–16 years. Participants' VSWM, visuospatial reasoning, and arithmetic abilities were assessed using standardized assessments. A subset of participants also took part in an fMRI scan while performing a VSWM task. Their results showed that VSWM and visuospatial reasoning correlated positively with arithmetic performance, but there was no relationship with age. However, there were developmental differences in brain activation, with increased activation in the left parietal sulcus relative to the rest of the brain predicting *poorer* arithmetic performance 2 years later, but greater activation in the whole brain VSWM network predicting better arithmetical performance.

Whereas Dumontheil and Klingberg's (2012) study investigated VSWM and associated brain activation trends with respect to mathematics, others have sought to explore the relationship between mathematical performance and the type of working memory employed as children grow older. Soltanlou, Pixner, and Nuerk (2015) conducted a study in which children in grades 3 and 4 were assessed on both verbal and visual working memory tasks and their multiplication skills. As observed in other studies, results showed that, overall, children's working memory skills increased with age. However, they also found that while verbal working memory was a predictor of multiplication problem solving ability in grade 3, it was not predictive of performance in grade 4. The opposite was true for VSWM, being a predictor of performance in grade 4, but not in grade 3. According to Soltanlou and colleagues, these results are consistent with other studies showing a weak connection between the phonological loop and mathematical ability in adults versus children. The implication is that the verbal component of working memory is important when younger children are learning math skills, but that as they develop, their understanding of mathematics becomes more abstract and visually based. Results such as these show the general developmental trends seen in VSWM have a complex interaction with children's mathematical abilities and cognition.

Conclusions

Overall, research indicates the important role of the parietal lobe in general visuospatial cognition, but also the dominance of the right hemisphere with respect to certain visuospatial skills. Other brain areas related to visuospatial cognition include

the superior frontal gyrus/sulcus, anterior insular cortex, temporal-occipital cortex, dorsolateral prefrontal cortex, precentral gyrus, and left hemisphere dorsal anterior cingulate cortex.

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