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

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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.

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