



Charting the diversity of strategic processes in visuospatial short-term memory

Corentin Gonthier

► To cite this version:

Corentin Gonthier. Charting the diversity of strategic processes in visuospatial short-term memory. Perspectives on Psychological Science, 2021, 16 (2), pp.294-318. <10.1177/1745691620950697>. <hal-03288849>

HAL Id: hal-03288849

<https://hal.science/hal-03288849v1>

Submitted on 26 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Charting the diversity of strategic processes in visuo-spatial short-term memory

Corentin Gonthier

Université Rennes 2

Corentin Gonthier, Univ. Rennes, LP3C EA 1285, Rennes, France

Correspondence concerning this article should be addressed to Corentin Gonthier,
Laboratoire LP3C, Campus Villejean, Place du Recteur Henri Le Moal, CS 24307, 35043
Rennes Cedex, France

E-mail: corentin.gonthier@univ-rennes2.fr

Word count : 18.267 words excluding title page, abstract, figures and tables

Abstract

Despite the abundant literature on visuo-spatial short-term memory, researchers have devoted little attention to strategic processes: what procedures do subjects implement to memorize visuo-spatial material? Evidence for various strategies exists, but it is spread across a variety of fields. This integrative review of the literature brings together scattered evidence to provide an overview of strategic processes in visuo-spatial tasks. The diversity of strategies is reviewed, as well as their proposed operating mechanisms. The evidence leads to proposing seven broad strategic processes used in visuo-spatial short-term memory, each declined in multiple variants. Strategies can vary across individuals, but the same subjects also appear to use multiple strategies, depending on the perceptual features of to-be-remembered displays. These results point to a view of visuo-spatial strategies as a functional library of facilitatory processes, on which subjects can draw to support visuo-spatial short-term memory performance. Implications are discussed for the difference between visual and spatial tasks, for appropriate measurement of strategic behaviors, and for the interpretation of performance in visuo-spatial memory tasks.

Keywords

Visuo-spatial memory; Strategy use; Short-term memory; Working memory; Functional processes

Public Significance Statement

This integrative review indicates that a broad range of strategic processes are used concurrently to support performance in visuo-spatial short-term memory tasks. The results support the view of memory performance as the result of multiple processes operating in tandem, some of which are very similar across visual and spatial tasks. Variability in strategy use can affect patterns of behavior and performance in visuo-spatial tests, with implications for clinicians and researchers alike.

Memory tasks are often performed using mnemonic strategies – methods or procedures, conscious or not, that help participants perform the task adequately (Lemaire & Reder, 1999). Although strategies are frequently overlooked in favor of studying only total scores, strategy use constitutes a key causal mechanism connecting individual ability to performance in a task (e.g. Gonthier & Roulin, 2019; see also Simmering & Perone, 2013): when using different strategies, two participants with the same level of ability can be expected to demonstrate different patterns of brain activity, different patterns of behavior, and ultimately different scores. These differences can bias results (Siegler, 1987; Logie, 2018) and create inconsistencies in the literature (Pearson & Keogh, 2019). For these reasons, understanding strategy use is critical to understanding together how people manage to remember visuo-spatial material over a short duration. This is all the more true that visuo-spatial tasks are particularly liable to elicit multiple strategies (Glück, Quaiser-Pohl, & Neubauer, 2010), even when they seem relatively simple (Shah & Miyake, 1996).

Many authors have reported scattered evidence in favor of one strategy or another, but few studies have been specifically interested in strategy use in visuo-spatial short-term memory (STM). As a consequence, even coming up with a tentative list of possible visuo-spatial STM strategies is not at all straightforward. By contrast, strategies in verbal STM, such as subvocal rehearsal, are more well-known (e.g. Dunlosky & Kane, 2007; Morrison, Rosenbaum, Fair, & Chein, 2016; Turley-Ames & Whitfield, 2003). For this reason, recent works have called for greater attention to this particular aspect of cognitive processing: for example, Pearson and Keogh (2019) proposed that inconsistencies in the literature could be resolved by considering that the nature of a visuo-spatial STM task fundamentally changes as a function of the strategies used to solve it. Similarly, Brown Nicholls and English (2019) concluded that older adults differed from younger subjects in their patterns of visuo-spatial STM strategy use, potentially contributing to age-related decline in performance. Both

studies pointed to strategy use as a key factor in understanding visuo-spatial memory performance, stressing the need for closer examination of visuo-spatial strategies.

Diversity of Strategies in Visuo-Spatial Memory

A cursory reading of the literature may convey the impression that visuo-spatial STM tasks (or visuo-spatial working memory tasks; the two will be considered together here) can be solved exclusively through either a purely visual or a verbal recoding strategy. Indeed, many researchers have mostly focused their discussion of visuo-spatial strategy use on the distinction between visuo-spatial encoding and verbal recoding (e.g. Brown Nicholls & English, 2020; Pearson & Keogh, 2019). This may be in part because it is strikingly clear that visual and verbal recoding strategies involve different mechanisms, in part because it fits well with common conceptions of working memory as constituted of separate verbal and visuo-spatial store systems (e.g. Logie, 2011), and in part because several impactful works have been devoted to the interplay between the two strategies, including the progressive emergence of verbal recoding throughout development (Pickering, 2001; Hitch, Halliday, Dodd, & Littler, 1989; Hitch, Halliday, Schaafstal, & Schraagen, 1988). Critically, however, this does not imply that strategy use is restricted to these two possibilities (see e.g. Brown Nicholls & English, 2020).

The handful of studies that have collected explicit self-reports of strategy use provide a first window into the diversity of strategy use (Brown Nicholls & English, 2020; Kirchhoff & Buckner, 2006; Magen & Berger-Mandelbaum, 2018; Patt et al., 2014; Ridgeway, 2006; Smith, Ritzhaupt, & Tjoe, 2010; Strasser et al., 2010). These studies have identified as many as 10 different strategies for visuo-spatial STM (Kirchhoff & Buckner, 2006). One example is the study of Patt and colleagues (2014), which used a version of the Corsi block-tapping task. Out of 25 subjects, 22 reported linking targets in their mind using imaginary lines and

memorizing the corresponding shapes, 5 counted the targets, 1 recoded spatial positions verbally, 1 recoded spatial positions as audio tones, and 1 used finger movements to retrace the sequence of stimuli. With these examples of spontaneous strategies reflecting a mix of analytic, holistic, verbal and auditory recoding, and kinesthetic behaviors, the results of self-reports confirm that strategy use is more complex than a simple distinction between visuo-spatial and verbal processing.

One factor that could lead to underestimating the breadth of strategic processes is vagueness on what exactly constitutes a strategy. Some visuo-spatial strategies can require complex conscious elaboration, possibly contributing to the strong involvement of cognitive control in visuo-spatial STM tasks (Bor, Duncan, & Owen, 2001; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Shah & Miyake, 1996). In other cases, there is a fine line between strategic and automatic processing, and some of the evidence reviewed in the next section may be seen as reflecting automatic perceptual/mnesic mechanisms rather than strategic memory processes as such (see also Jones, Hughes, & Macken, 2006). A good example is symmetry-based chunking: perception of vertical symmetry is relatively automatic, and symmetry benefits recall even in very young children (Bornstein & Stiles-Davis, 1984) and even in dual task situations (Rossi-Arnaud et al., 2006). This could indicate that encoding the display as a symmetrical picture is an automatic phenomenon naturally emerging from a perceptual regularity of the display, rather than a strategic process per se. On the other hand, some participants explicitly self-report "making use of symmetry to remember", indicating conscious awareness; when asked to generate their own visuo-spatial displays for future recall, they tend to voluntarily arrange stimuli in symmetrical patterns (Magen & Berger-Mandelbaum, 2018); and when recalling a symmetrical display, they almost always recall one half first before reproducing the other half by symmetry (Bornstein & Stiles-Davis, 1984), all of which are more consistent with a strategic process. Based on the

classic definition of strategies as procedures used by participants to help perform the task, whether consciously or not (Lemaire & Reder, 1999), this example of symmetry-based chunking to support recall certainly qualifies as a strategy.

Charting Possible Strategies in Visuo-spatial Memory

This integrative review considered all studies that provided insight into processes used to encode, maintain and recall visuo-spatial stimuli after a short duration (< 1 minute), independently of the population, type of to-be-remembered stimuli, or details of the paradigm. A procedure was considered to qualify as a "strategy" if it met the following three criteria: 1) it constituted a tractable set of cognitive or sensory-motor operations affecting the encoding or maintenance of memory traces; 2) it was not mandatory (subjects could use this procedure or not), indicating that it reflected an additional process used to scaffold performance above and beyond the basic functioning of visuo-spatial STM; 3) it was conscious or at least amenable to consciousness, as reflected in subjective verbal reports. For instance, "recode pictures verbally" was considered as a strategy: it is an optional cognitive operation which influences the representation of stimuli in memory, of which participants are conscious, and which affects performance. Conversely, "allocate attention to stimuli during encoding" was not considered a strategy because it constitutes an integral part of intentional STM. Highly specific strategies applying only to a particular paradigm were not included. All strategies considered here appeared liable to impact recall performance, making them important processes to consider in understanding visuo-spatial STM.

For the purposes of this review, major strategies found in the literature were organized in eight categories, broadly corresponding to different types of processes. In other words, strategies that appeared to tap into similar mechanisms were grouped together, in an effort both to provide a useful nomenclature and to shed some light on the processes underlying

STM. There is significant overlap between certain categories, because some strategies can tap into multiple processes – this point is discussed in further detail in the next sections. An overview of the strategies listed here is provided in Table 1. Many studies have used variants of the visual patterns task (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999) or the Corsi block-tapping task (Corsi, 1973); an illustration of both paradigms is presented in Figure 1, along with examples of the eight categories of strategies, which interested readers can try out for themselves.

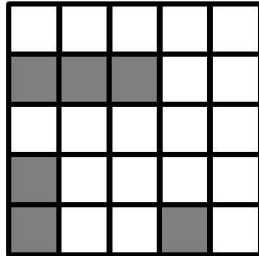
Table 1. *Overview of the major strategic processes recruited by visuo-spatial STM tasks and examples of implementation.*

Strategic process	Examples of implementations
1. Chunking	Memorize spatially close stimuli together Memorize temporally close stimuli together Memorize similar stimuli together Memorize geometric shapes Memorize meaningful shapes (letters...) Memorize symmetrical targets together
2. Holistic encoding	Encode all stimuli as a unitary picture Encode the shape of the path between stimuli Construct a story to describe the whole picture Keep the gaze fixed on the center of the screen
3. Relational encoding	Encode the position of stimuli in relation with the reference frame Encode the position of stimuli in relation with each other Encode the position of stimuli in relation with a landmark
4. Subdivision and categorical encoding	Divide the reference frame into sub-parts Divide a set of stimuli into sub-parts Divide a sequence of stimuli into sub-parts
5. Recoding	Verbal recoding : attach names to stimuli Verbal recoding : describe the display with a sentence Verbal recoding : use of system of coordinates Kinesthetic recoding : retrace a sequence of stimuli Kinesthetic recoding : retrace the outlines of the shape of stimuli Other recoding, such as auditory recoding
6. Long-term memory, semantic or episodic	Construct a meaningful story (holistic) Memorize meaningful configurations (chunking) Assign meaningful names to stimuli (verbal recoding) Use memories of configurations from previous trials
7. Visuo-spatial rehearsal	Rehearse the path between stimuli in a sequence Mentally refresh the visual image of the display
8. Others	Count the total number of stimuli Bind the stimuli in a sequence with digits Mental reduction of the encoding space Selective encoding of certain stimuli

Figure 1

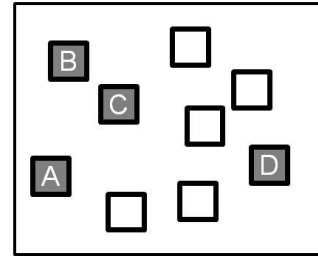
Illustration of two common paradigms for visuo-spatial short-term memory, with examples of

(a)



1. Chunking : memorize the three horizontal squares as a single line
2. Holistic encoding : try to photograph the whole picture in your mind
3. Relational encoding : remember that the horizontal line is 1 square from the top
4. Subdivision : remember 3 squares in the top half and 3 in the bottom half
5. Recoding : say to yourself *three in a line, two vertically below, one on the right*
6. Long-term memory : imagine a tree with a fallen fruit below
7. Visuo-spatial rehearsal : mentally redraw the picture (e.g. with eyes closed)
8. Others : count that there are 6 squares to remember

(b)



1. Chunking : remember that the 2nd and 3rd block are next to each other
2. Holistic encoding : remember that the path makes the shape of an inverted V
3. Relational encoding : remember that the first two blocks are in corners of the frame
4. Subdivision : divide the sequence into a "left-side" (ABC) and a "right-side" (D) part
5. Recoding : use your index finger to retrace the path
6. Long-term memory : remember that the sequence resembles the previous trial
7. Visuo-spatial rehearsal : mentally retrace the path between locations
8. Others : think *one* when looking at the first block, *two* for the second block, etc.

possible strategies

Note. (a) Visual patterns test, where all targets appear simultaneously in a structured grid; (b) Corsi block-tapping task (using the standardized arrangement from Kessels et al., 2000), where locations are marked in a sequence (noted as A-B-C-D here). The examples of strategies provided below were sampled from Table 1 for illustration, and are not an exhaustive list of all strategies possible for these items.

1. Chunking strategies.

A first possible type of visuo-spatial encoding strategy is chunking: grouping or organizing individual targets into chunks. This process has been largely studied in the field of verbal short-term memory, but there is overwhelming evidence that it also takes place in visuo-spatial STM. Recoding a large number of targets into a smaller number of chunks decreases the number of separate information tokens to be memorized and recalled, thus increasing memory capacity (Miller, 1956; see also Thalmann, Souza, & Oberauer, 2018). Delvenne and Bruyer (2006) note another potential benefit of chunking in the context of visuo-spatial STM: by decreasing the number of stimuli, it also decreases the number of relations between stimuli to be memorized, and thus the overall complexity of the display. The field of visuo-spatial memory has often made a distinction between visual memory (dedicated to memorizing static patterns of visual information) and spatial memory (dedicated to memorizing sequences of spatial positions); chunking appears to take place for both static visual material and sequences of spatial locations (Schumann-Hengsteler et al., 2004).

Chunking in visuo-spatial STM appears to be primarily based on spatial proximity, which stems logically from Gestalt principles stating that objects that are spatially close tend to be grouped together (Wagemans et al., 2012). Woodman and colleagues accordingly showed that items grouped by proximity during encoding tended to be stored in memory together (Woodman, Lecera, & Luck, 2003); this improved performance, as cueing a given item elicited better recall for the other items with which it was grouped. Overall, subjects tend to demonstrate better performance for displays where objects or features of objects are spatially grouped during encoding (Xu, 2006; Xu & Chun, 2007). Note that this process of chunking does not strictly have to be conscious: when items are regularly presented together

over the course of multiple trials, subjects can implicitly learn them as chunks, without conscious awareness (Brady, Konkle, & Alvarez, 2009; Orbán, Fiser, Aslin, & Lengyel, 2008). Even over a relatively small number of trials, subjects can benefit from grouping without being aware of it (Xu & Chun, 2007). Chunking can also be an intentional process, potentially involving regions of the dorsolateral prefrontal cortex (Bor et al., 2001).

An added layer of complexity to the process of chunking comes from the nature of the chunks stored by subjects – their representation in memory. Indeed, there is evidence that items are not necessarily memorized just as "groups": participants seem to benefit particularly from recognizable configurations of targets, such as diagonal lines or T-shapes (Dai, Thomas, & Taylor, 2018). This can help subjects encode and/or recall the chunk, in that knowledge of the overall shape of the group of items means that recall can proceed through pattern completion based on only a few items of the group (see Uttal & Chiong, 2004).

It is also noteworthy that chunk representations are not limited to simple geometric shapes: even when memorizing simple squares in a matrix, subjects can take advantage of elaborate configurations resembling animals, faces, simple objects, letters, or even maps (Brown, Forbes, & McConnell, 2006; see also Avons & Phillips, 1987; Pickering, 2001). This is true for both configurations occurring in randomly generated stimuli (Brown et al., 2006) and for targets purposefully arranged in a meaningful shape (Uttal & Chiong, 2004). These results suggest that subjects can ascribe semantic meaning to a visuo-spatial chunk, further facilitating encoding.

Although the process of chunking in visuo-spatial STM appears to be largely dependent on spatial proximity (Peterson & Berryhill, 2013), it seems that other gestalt principles can contribute as well. Ridgeway (2006) reported temporal grouping for sequences of spatial locations, with subjects chunking consecutive locations in the sequence (e.g. the first three locations together, then the next three locations), although this was enhanced when

successive targets were actually spatially close. Similar objects tend to be chunked together, at least if they are sufficiently close (Peterson & Berryhill, 2013); when remembering colored targets in a matrix, perceptual grouping tends to occur for targets with the same color (Morey, 2019). Connectedness between items may also play a role (Xu, 2006).

Of particular interest in visuo-spatial STM tests is the principle of symmetry: recall is improved when the configuration of stimuli is symmetrical (Howe & Jung, 1986; Rossi-Arnaud, Pierroni, & Baddeley, 2006; Rossi-Arnaud, Pieroni, Spataro, & Baddeley, 2012). Vertical symmetry seems more helpful than diagonal or horizontal symmetry, although these can also improve performance to a lesser extent (Rossi-Arnaud et al., 2006, 2012). When patterns of stimuli are vertically symmetrical, subjects almost always recall half of the screen first before reproducing the other half along the axis of symmetry (Bornstein, & Stiles-Davis, 1984), which suggests that symmetrical stimuli are memorized as a chunk. Again, this is not limited to simultaneous presentation of targets, as several studies have suggested better recall for sequences of targets forming a symmetrical path (Imbo, Szmalec, & Vandierendonck, 2009; Kemps, 2001).

2. Holistic strategies.

As a second type of possible strategy, subjects can try to encode all targets (all features of the display) as a single visual image, a global configuration (Lecerf & De Ribaupierre, 2005). The holistic strategy is a close relative to chunking, and could be viewed as an extreme form of chunking wherein all items are chunked together to form a single image (by contrast, the term *chunking* usually refers to creating a sub-group with only part of the stimuli). Visuo-spatial STM tasks where stimuli are presented simultaneously are often described as requiring subjects to memorize a (singular) visual pattern (e.g. Della Sala et al., 1999; Logie & Pearson 1997), although this is not always made explicit in the literature.

Logie (1995, p. 78) further makes it clear that "to retain a purely visual representation of a scene there need be no distinction between an array of several objects and a visual display of a single object which has a number of components".

This idea of subjects forming a holistic representation of visuo-spatial material has been discussed more extensively in the context of scene perception, but also extends to memory for visual displays (see Rensink, 2000, on coherence theory). Rensink (2000) discussed the formation of a holistic representation as binding several objects within a coherent representation, wrapped in a "nexus" which comprises a summary description of the display. This coherent representation can be extended beyond the objects themselves to additionally include information about the setting of the visual display, representing the gist and/or the layout of the scene. This coherent representation could then form the basis for memory of visual scenes (Rensink, 2000), and could be helpful for recall due to both the enclosed summary description of the display (which could help identify and retrieve forgotten stimuli), and the additional information about the gist or layout of the scene (which could help retrieve the relative locations of stimuli).

A holistic-analytic strategy continuum has often been described in other areas of visual information processing: for example, subjects performing mental rotation can process each part of the to-be-rotated shape separately (analytic strategy), or try to mentally rotate the shape as a whole (holistic strategy; see e.g. Glück & Fitting, 2003). Visual exploration can also be performed using a local or global strategy (e.g. Hogeboom & van Leeuwen, 1997). In the context of visuo-spatial long-term memory, several studies using the Rey-Osterrieth complex figure (a complicated drawing which comprises 18 elements arranged in an organized configuration, lending itself to memorization of individual elements and/or of their broad arrangement) have described a dissociation between analytic and holistic encoding strategies (Bennett-Levy, 1984; Rosenbloom, Sassoon, Pfefferbaum, & Sullivan, 2009;

Sullivan, Mathalon, Ha, Zipursky, & Pfefferbaum, 1992). Direct evidence for the encoding of visuo-spatial displays as a singular picture in STM is a little scarcer.

One study (Berger & Gaunitz, 1979) required subjects to keep pictures in memory for a very short duration in order to perform a comparison task, and identified two strategies: picking out details of the pictures for comparison (analytic), or making up a mental image of the whole picture (holistic). The whole-image holistic strategy appeared for approximately half the sample, although it was used somewhat less consistently than the analytic strategy; the holistic strategy also appeared to be less effective. As a variation on making a mental image of the picture, some subjects also reported trying to "get the feeling of the picture" or "feel the atmosphere of the picture". Another study using recognition of visual patterns (Cocchi et al., 2009) found that subjects, especially patients with schizophrenia, tended to make false alarm errors for new patterns whose global shape resembled learned patterns, suggesting encoding of the overall picture rather than individual details.

Another clue in favor of a holistic strategy is found in studies assessing eye movements in visuo-spatial STM tasks. It is well-known that eye movements towards to-be-memorized targets accompany covert shifts of attention (e.g. Pearson & Sahraie, 2003; see also the section on visuo-spatial rehearsal below). Subjects are sometimes observed to keep their gaze fixed on the center of the screen during encoding, in a way that allows them to see all items simultaneously (Lange & Engbert, 2013; Morey, Cong, Zheng, Price, & Morey, 2015; Patt et al., 2014); this may reflect an attempt to use a holistic strategy and encode the whole display as a unitary picture (for alternatives, see Lange & Engbert, 2013). Subjects explicitly report choosing to fix their eyes on the center of the screen in verbal reports, indicating that this constitutes a conscious strategy (Pearson & Sahraie, 2003). Relatedly, subjects are sometimes observed to fix the center of a to-be-remembered complex visual pattern, and this behavior is related with the tendency to confuse learned patterns with

patterns displaying a similar global shape during a recognition phase - again suggesting holistic encoding (Cocchi et al., 2009).

A specific form of holistic strategy can be observed when subjects attempt to imagine a sequence of spatial locations as a single path, a single shape connected by imaginary lines (e.g. Ridgeway, 2006). Such a strategy has been observed in close association with the pattern of keeping the gaze fixed at the center of the screen (Patt et al., 2014). Other studies found better recall when the path formed by a series of targets made a recognizable shape (Imbo et al., 2009; Kemps, 2001; see also Zoelch & Schumann-Hengsteler, 2006; Schumann-Hengsteler, Strobl, & Zoelch, 2004). The fact that this strategy was observed in studies using sequential presentation of stimuli highlight the possibility of using holistic strategies, even when the targets integrated in a single mental image are not presented simultaneously.

A variant of holistic encoding is found in the work of Kirchhoff & Buckner (2006), who had subjects memorize pictures made of a combination of objects. Some subjects reported constructing a story to explain what was occurring in the picture, which constitutes a form of holistic strategy assigning meaning to the to-be-remembered display as a whole. In this case, a holistic strategy is combined with semantic information.

3. Relational encoding strategies.

Another way to encode visuo-spatial information is to memorize the relations between elements of the visual display, so as to support recall of their relative positions. Avons (2007) studied this process in a Corsi-like task and showed that spatial locations were encoded relative to the frame of reference: moving the frame of reference on the screen (the workspace along with the Corsi blocks it contained) between the presentation of each location during encoding impaired recall. Conversely, recall performance improved when successive trials kept the stimulus positions relative to the frame of reference constant while

moving their absolute positions on the screen. These results demonstrate that participants encode the relative position of stimuli; this is open to strategic variability, given that various aspects of the display can be used as relational points of reference.

On one hand, subjects can try to encode the position of items relative to the reference frame itself - especially the edge of the grid in which spatial locations appear (Lecerf & De Ribaupierre, 2005). In this case, subjects can use the strategy of encoding position in the form of distances to the edge, or spatial coordinates (Kosslyn, 1987; Schumann-Hengsteler et al., 2004; Strasser et al., 2010). Hartley and colleagues concluded that encoding for the relative position of a stimulus is best approximated as a function of its proximity to all four edges of the reference frame; "proximity" would be defined as the fixed distance to the closest edge when the stimulus is close to an edge, and as the relative distance between opposite edges when the stimulus is closer to the middle of the frame (Hartley, Trinkler, & Burgess, 2004).

There is also overwhelming evidence that subjects encode the position of items relative to each other. Multiple studies have shown that visuo-spatial STM can be configuration-based, and that the identity of a stimulus and its position relative to other stimuli are spontaneously integrated in memory (Clevenger & Hummel, 2014; Treisman & Zhang, 2006). In particular, changing the configuration of objects surrounding a target probed for recall consistently impairs performance (Blalock & Clegg, 2010; Chun & Jiang, 1998; Jiang, Olson, & Chun, 2000). Conversely, recall is better if the context in which an item is to be recalled matches the encoding context (Jiang, Chun, & Olson, 2004; Silvis & Shapiro, 2014). Likewise, shifting the absolute position of an item on the screen does not impair recall if the relative configuration of items is preserved (Blalock & Clegg, 2010; Hollingworth, 2007). In the case where spatial locations are presented sequentially, the location of the first target receives the most attention, and subjects frequently look back towards this location; this suggests that the first item can act as a sort of anchor, with the location of other targets

encoded in reference to this one (Lange & Engbert, 2013). Note that this relational encoding seems to be a strategic process, rather than an automatic feature of visual processing (Udale, Farrell, & Kent, 2018; Woodman, Vogel, & Luck, 2012). Attention usually appears to be necessary for the encoding of relations between items, although this can vary across paradigms (Gmeindl, Nelson, Wiggin, & Reuter-Lorenz, 2011; Jiang et al., 2000, 2004; Rashal, Yeshurun, & Kimchi, 2017).

Relational encoding can also be based on landmarks: specific features of the visual display that serve as reference points. When landmarks are present, they elicit an attraction effect (see e.g. Hubbard & Ruppel, 2000): targets are recalled as being closer to the landmark than they actually were at encoding. Most studies have investigated this effect by explicitly adding landmarks to the encoding context, but participants may conceivably self-designate their own landmarks. Features of the display, such as the corners of the encoding grid, could serve this role: targets presented near the corners require less effort to be encoded (Starc, Anticevic, & Repovs, 2017; see also Hartley et al., 2004). Conspicuous configurations of items, such as a large chunk of items, could also be used as landmarks. For example, one study on recall of colored targets showed that subjects prioritized looking at duplicate colors during encoding and at the location of unique colors during the retention of interval, suggesting that subjects use the location of duplicate colors to structure their encoding of the display (Morey et al., 2015).

4. Strategies involving subdivision and categorical encoding of the stimuli.

Visuo-spatial displays often present highly complex stimuli that can be difficult to analyze and encode in a limited time. One way to facilitate encoding is to divide the display or reference frame in several sub-parts, and to encode spatial locations as a function of the subpart in which they appear. For example, participants can operate based on division of the

grid of locations in four quadrants (Huttenlocher, Hedges, & Duncan, 1991; Huttenlocher, Hedges, Corrigan, & Crawford, 2004; Starc et al., 2017). In this case, responses tend to be shifted towards the nearest angle.

This strategy can be viewed as a form of categorical encoding (Postma, Kessels, & van Asselen, 2004), with the targets being encoded as belonging to a particular category, such as the "bottom right part of the grid". Such categorical encoding – in contrast with precise encoding of spatial location – is often found in studies of visuo-spatial memory (see Newcombe & Huttenlocher, 2007). Kosslyn and colleagues (Kosslyn, 1987; Kosslyn et al., 1989) explicitly conceived visuo-spatial encoding as the combination of a categorical system providing coarse information for location, and a more precise coordinate system (see also Bruyer, Scailquin, & Coibion, 1997; Hellige & Michimata, 1989). This idea has been extended in recent models of memory for object locations (Postma et al., 2004, 2008), and is supported by dissociations in neuropsychological studies and neuroimaging: coarse categorical and precise coordinate-based encoding appear to have different neural substrates (see Zimmermann & Eschen, 2017).

Instead of decomposing the reference frame itself, a possible variant of this strategy, found in memory for complex visual patterns, is to break down to-be-remembered stimuli (see also Kosslyn, 1987, for a discussion of mechanisms involved in the mental representation of sub-parts of visuo-spatial stimuli). The sub-parts of the stimulus can then be memorized as separate chunks of information. Examples of this strategy have appeared in studies requiring participants to memorize complex abstract shapes (Kyllonen, Lohman, & Woltz, 1984; Smith et al., 2010). In one study (Smith et al., 2010), subjects explicitly reported dividing the shape into smaller pieces and memorizing these smaller pieces separately (a strategy labeled "divide and conquer" by the authors). This process appears to be an inverted form of the chunking strategy discussed above: the stimulus is initially

perceived as a whole, and is then decomposed into sub-parts which are memorized separately. Like decomposing the reference frame, this can be a way to provide coarse categorical information about major pieces of to-be-remembered information.

Another form of subdivision of stimuli is found in memory for sequences of spatial locations. When stimuli appear sequentially, some subjects can choose to break down the sequence into smaller sub-sequences memorized separately (Ridgeway, 2006; again, this strategy is intimately tied with chunking.) This division can be accompanied by verbal labeling of stimuli, which presumably helps parse the sequence into sub-sequences ("one, two, three, one, two, three"; see Ridgeway, 2006). This division may be particularly helpful when the overall sequence of locations is constituted of several subgroups of locations that are close to one another: in this case, subdivision could facilitate encoding the shape of the overall path (see Imbo et al., 2009; Kemps, 2001; Zoelch & Schumann-Hengsteler, 2006; Schumann-Hengsteler et al., 2004).

5. Recoding strategies.

Verbal recoding is a well-known strategy for the encoding of visual material. Hitch and colleagues have demonstrated that this strategy emerges early in development, with children as young as 8 years old being sensitive to the length of the name of to-be-remembered pictures; this indicates that the pictures are named and that these names are then rehearsed subvocally (Hitch et al., 1988, 1989). Critically, verbal recoding is not limited to pictures of concrete objects: abstract visual patterns selected to be easier to recode verbally elicit higher recall performance (Brown et al., 2006; Brown & Wesley, 2013). Such verbal recoding may partly explain why secondary tasks involving verbal materials interfere with maintenance of visual and spatial materials in dual-task paradigms (for a meta-analysis, see Morey, 2018).

Attaching verbal labels to visual displays makes it possible for the participant to tap into verbal memory in addition to visuo-spatial memory, and thus to use subvocal rehearsal; this could mechanically improve performance if the two are viewed as distinct systems (Logie, 2011). However, the benefits of verbal recoding can also extend beyond simple rehearsal. Several possibilities have been proposed (see Souza & Skóra, 2017): verbal recoding could also be a way to add a verbal representation to the visuo-spatial representation in memory, thus constituting a form of dual coding (Paivio, 1991); it could be used as a retrieval cue (Souza & Skóra, 2017); or it could be a way to elaborate memory traces by tapping into semantic knowledge (Brown & Wesley, 2013). The latter solution seemed most consistent with the data in one study (Souza & Skóra, 2017), but all of these could be true to an extent.

Importantly, the process of verbally recoding visuo-spatial material does not stop at naming pictures and rehearsing picture names, and can lend itself to more complex strategies. Participants in one study who had to memorize pairs of objects reported "saying the name of each object to myself", "using the starting letter of the names of the objects", and "constructing sentences that described the pictures" (Kirchhoff & Buckner, 2006). The latter strategy of constructing sentences can also be used to describe sequences of movements or directions ("up, down, left, right") in tasks where spatial locations appear sequentially (Patt et al., 2014). Some subjects also remember elaborate verbal descriptions based on coordinate systems (of the form "two fields left, one up, 3 backwards"; see Strasser et al., 2010).

Apart from verbal recoding, there is also substantial evidence for kinesthetic recoding: transforming spatial material into a sequence of movements. The strong conceptual similarity between visuo-spatial information and spatial movements was highlighted by Logie (1995), who reported "using the term spatial [to] refer to a representation that involves movement in its broad sense, to incorporate imagined movement as well as physical movement. This

movement could be in the form of scanning a visual array (via perception or scanning a mental image), or movement to a target in the array (with or without visual input), or movement of objects in an array." In this sense, spatially directed movements and spatial locations may point to a common mental representation, perhaps as a form of topographical map (Ikkay & Curtis, 2011; Quinn & Ralston, 1986).

Consistent with this idea, subjects sometimes self-report using finger movements to retrace a sequence of spatial stimuli (e.g. Patt et al., 2014), and motor and visuo-spatial memory tasks share part of their neural substrate (Faw, 2003; Ikkay & Curtis, 2011). Conversely, imposing concurrent body movements during the retention interval consistently interferes with memory, especially for sequences of spatial locations (e.g. Logie & Marchetti, 1991; Quinn & Ralston, 1986), and disrupting motor areas affects visuo-spatial STM performance (Liao, Kronemer, Yau, Desmond, & Marvel, 2014). The finding of a kinesthetic recoding strategy is reminiscent of the idea that rehearsal in STM can be viewed as a sequence of gestural actions (Jones et al., 2006), which suggests that movements can play the same role for spatial STM as articulatory rehearsal for verbal STM. Again, this kinesthetic encoding strategy is not limited to memory for sequences of locations, as subjects asked to memorize complex shapes have reported outlining the shape with their fingers (Smith et al., 2010).

The use of a beneficial kinesthetic recoding strategy may be seen as conflicting with the literature showing that asking participants to point at to-be-remembered locations during encoding decreases performance (e.g. Spataro, Marques, Longobardi, & Rossi-Arnaud, 2015). However, there may be an important distinction between imposed pointing movements and self-initiated pointing movements: the former may interfere with spontaneous strategy use and prevent participants from developing and using other beneficial strategies

(for a discussion, see Rossi-Arnaud, Spataro, & Longobardi, 2012), while the latter – performed with little effort or awareness – would leave spontaneous strategy use intact.

Recoding of visuo-spatial information in forms other than verbal and kinesthetic is certainly possible, although support for these other forms of recoding is more anecdotal. One subject in the study of Patt and colleagues (2014) reported recoding spatial locations into audio tones; I have anecdotally encountered similar self-reports in work from my own lab, with subjects recoding spatial locations closer to the top of the reference frame as tones with a higher pitch. One subject with particular musical expertise reported recoding spatial locations in a 6x6 matrix as chords written as guitar tabs.

6. Strategies based on long-term memory: semantic labeling and episodic memory.

Subjects can attempt to associate short-term memory traces of visuo-spatial displays with information stored in long-term memory. Avons and Phillips (1987) formalized this idea by suggesting that visuo-spatial displays are encoded through a combination of low-level processing of the targets, which can be stored in STM, and a semantic description of the display configuration based on prior knowledge stored in long-term memory. Likewise, Hitch and colleagues (Hitch, Brandimonte, & Walker, 1995) proposed that visuo-spatial STM tasks make use of both STM to encode surface visual information, and long-term memory to encode an abstract description of the display in addition to surface visual information. Logie (2011) argued that working memory holds both the product of perception and activated representations in long-term memory.

This process is clearly used when stimuli explicitly evoke semantic knowledge. For example, one study showed that Chinese-speaking subjects remember meaningful Chinese characters better than pseudo-characters, and that increasing the complexity of meaningful characters had no effect on performance, contrary to complexity of pseudo-characters (Sun,

Zimmer, & Fu, 2011). A similar example is found in classic research on expert chess players, who are better able to remember the location of chess pieces on a chessboard (Chase & Simon, 1973), but only when they are arranged in legitimate configurations (see Lane & Chang, 2018). In both cases, semantic knowledge is tapped to provide a label for the visuo-spatial display, which is much simpler to memorize than a complex display of visuo-spatial stimuli – but it is debatable whether this process is strategic or purely automatic.

Importantly, however, semantic labeling does not stop with meaningful stimuli, as a number of studies have reported subjects remembering abstract visual stimuli through explicit elaboration and association with familiar objects (e.g. Smith et al., 2010). In this case, stimuli resembling a meaningful object are explicitly recoded as this object, with the semantic labeling again facilitating recall. Two other forms of this strategy are found in the work of Kirchhoff and Buckner (2006): subjects reported constructing a meaningful story to describe and remember pictures of objects; they also reported using prior personal memories associated with the objects. In both cases, additional meaning is attributed to the to-be-remembered display to facilitate recall. Interestingly, meaningless visual patterns constituted of black and white squares also vary in their susceptibility to semantic labeling. Random visual patterns that are more nameable elicit higher performance (Brown et al., 2006; Riby & Orme, 2013), which can be interpreted as the result of a richer memory trace for these stimuli (Riby & Orme, 2013).

At least two types of strategies outlined above can make use of information stored in long-term memory: this is the case for both chunking strategies and holistic strategies, where the configuration of stimuli may match a template stored in long-term memory, and thus be ascribed additional meaning to facilitate memorization. The case where a group of stimuli is associated with a semantic label (e.g. "this group of targets looked like a spaceship") is thus a combination of a chunking or holism strategy, and a strategy of using long-term semantic

memory traces to support recall. When the semantic label is explicitly named by the subject (possibly to be subvocally rehearsed), these two strategies can also be combined with a form of verbal recoding.

Subjects can also make a different use of long-term memory by tapping, not into prior knowledge about meaningful shapes or patterns, but into episodic memory about preceding trials of the same task. When performing a series of trials in a STM task, part of a given trial can sometimes match a prior trial (because the location of a target, a group of targets or a sequence of targets is the same). Subjects may be able to recognize the match and use a long-term memory trace of the preceding trial to support recall for the current trial. In support of this possibility, Kemps (2001; Experiment 5) showed that sequences of spatial positions do leave a trace in long-term memory, so that even a single repetition of a trial elicits better recall. Such a long-term memory trace can then be exploited to a more or less conscious degree by subjects to facilitate encoding; this sometimes appears in verbal reports (such as "I remembered this configuration from before").

7. Visuo-spatial rehearsal strategies.

Subjects often remember verbal material by (subvocally) rehearsing during the retention period; it has long been suspected that a similar process takes place for visuo-spatial memory, allowing subjects to refresh memory traces (e.g. Logie, 1995). In Logie's account of visuo-spatial working memory, refreshing of the memory traces of both spatial locations and visual images is explicitly performed by the inner scribe component of the visuospatial sketchpad (see Logie, 2011). Mental rehearsing of a path between spatial locations presented sequentially appears very frequently in verbal reports (Patt et al., 2014; Ridgeway, 2006). Interestingly, some participants rehearse not only during the retention period, but also during encoding, by continually retracing the path between all locations as new locations appear

(Lange & Engbert, 2013; Ridgeway, 2006; see also Meiser & Klauer, 1999): in a task where spatial locations appear sequentially, maintenance is interleaved with encoding.

Several researchers have studied the mechanisms by which subjects rehearse visuo-spatial material. In order to refresh sequences of spatial locations in memory, subjects seem to focus their attention on to-be-maintained locations during the retention interval (Awh, Anillo-Vento, & Hillyard, 2001; Awh & Jonides, 2000), a form of attentional refreshing close to what is observed for verbal working memory (Mora & Camos, 2013). These successive shifts of attention towards to-be-remembered targets may be covert, or they may be accompanied by eye movements, especially when memorizing sequences of spatial locations (Patt et al., 2014; Pearson, Ball, & Smith, 2014; Pearson & Sahraie, 2003; Tremblay, Saint-Aubin, & Jalbert, 2006).

The role of eye movements during rehearsal is debated, and appears to be inconsistent across studies. Some authors have argued that eye movements play a critical role, with performance decreasing when they are prevented (Pearson et al., 2014), and benefit recall in particular when they are used to rehearse locations that have disappeared from the display (Czoschke, Henschke, & Lange, 2019). Others have argued that eye movements towards targets are unnecessary (Godijn & Theeuwes, 2012; Patt et al., 2014), or even detrimental (Pearson & Sahraie, 2003), especially when they are not self-initiated (Lange & Engbert, 2013; similar to pointing movements, Rossi-Arnaud et al., 2012). One possibility is that rehearsal is based on necessary covert attention shifts, which can be accompanied by optional eye movements; these eye movements could help improve serial recall without being strictly necessary (Patt et al., 2014; Tremblay et al., 2006).

Visuo-spatial rehearsing has often been considered in tandem with the visualization of a path between spatial locations (see Schumann-Hengsteler et al., 2004). Indeed, a major clue in favor of visuo-spatial rehearsal is the path length effect – the finding that recall

performance decreases as the distance between successive to-be-remembered locations increases. This effect has been attributed to rehearsal, with a greater spatial distance between targets increasing the time needed to mentally retrace the path (to rehearse the sequence), akin to the effect of word length for rehearsal of verbal material (Guérard, Tremblay, & Saint-Aubin, 2009; Parmentier, Elford, & Mayberry, 2005). Eye-tracking data also indicate that preventing fixation of to-be-remembered locations during the retention interval can abolish the path length effect, consistent with a rehearsal account (Guérard et al., 2009). The finding that increasing complexity of the path between locations decreases recall performance (e.g. Parmentier et al., 2005) may also be partly due to increased difficulty in rehearsing the sequence. On the other hand, recent data showing that the path length effect does not necessarily vary as a function of the duration of the retention interval (see Guérard & Tremblay, 2012) suggests that it may not uniquely reflect rehearsal and may be partly caused by the ease of perceptually grouping locations that are close to one another, thus also reflecting a form of chunking or holistic strategy.

Although visuo-spatial rehearsal has usually been considered in the context of memory for sequences of spatial locations, this process is also applicable to static visual displays (see Brown & Wesley, 2013; Logie, 2011). For example, a strategy of "mentally refreshing" the visual image was frequently self-reported by subjects in a visual pattern task (Brown Nicholls & English, 2020), confirming that visuo-spatial rehearsal can be performed for static visual information as well as spatial locations. In this case, visuo-spatial rehearsal apparently takes the form of mentally redrawing the image during the retention period. It is unclear whether, and to what extent, this process differs from rehearsal of a path between locations: mentally redrawing a visual pattern could also be construed as a form of path, for example to redraw the outlines of the pattern (see also Smith et al., 2010). One study found

that subjects learning simple pictures for immediate recognition tend to adopt a fixed scanpath: a fixed series of eye movements towards specific parts of the picture, which is then repeated as a cycle (Noton & Stark, 1971). The authors proposed that subjects construct a "feature ring" - a sensory-motor trace combining the features of the display and the cycle of eye movements required to scan these features, which can then be used for retrieval in memory. This process appears conceptually close to the rehearsal of a path between spatial locations, and could conceivably subtend mental refreshing of static visual images.**8. Other possible strategies.**

Other strategies suggested by the literature fit less well with the rest, but deserve a mention because they shed light on one particular aspect of visuo-spatial memory. One is the strategy of counting to-be-remembered targets, which is frequently reported by subjects (Brown Nicholls & English, 2020; Patt et al., 2014; Ridgeway, 2006; Strasser et al., 2010). This strategy can take somewhat different forms depending on the material. In tasks requiring memory for sequences of spatial locations, subjects seem inclined to attach a numerical verbal label to each successive location ("one", "two"...; Patt et al., 2014; Ridgeway, 2006). This could be viewed as a form of verbal coding, or perhaps as a way to help bind targets in their correct serial position (see Majerus, 2013). In tasks requiring memory for visual patterns, this can also take the form of counting the total number of targets, so as to know how many targets to recall – in total or in a given chunk (see Brown Nicholls & English, 2020; Strasser et al., 2010).

Another possible strategy is rationalization, or reduction, of the workspace. This phenomenon was reported by Kemps (1999): when some spatial locations in the reference frame are never used, subjects can exploit this regularity, benefiting recall. In effect, it appears that subjects are reducing the mental workspace in which stimulus encoding and/or recall operates: recall proceeds as if the grid was smaller than it actually is. It is unclear

whether this workspace reduction is at all a conscious strategy for most subjects (although it has on occasion emerged in unpublished verbal reports). This strategy may be rare in the literature simply because visuo-spatial STM laboratory tasks are often designed so that stimuli span the whole reference grid, leaving little opportunity for mental reduction of the workspace.

A special case is partial memorization of the visual display: in some studies, participants have demonstrated that they can strategically prioritize encoding of certain stimuli (Hu, Allen, Baddeley, & Hitch, 2016; see also Allen, Baddeley, & Hitch, 2014). This strategy may appear especially when memorizing certain stimuli in a sequence is associated with a particular reward (Hu et al., 2016), or for very difficult trials where set size exceeds the capacity of the subject (Allen et al., 2014). In the latter case, subjects can prioritize encoding particularly conspicuous features of the display (Smith et al., 2010), such as chunks of items, perhaps to use them as landmarks (Morey et al., 2015). Again, this strategy of partial memorization may be rare in the literature simply because STM tasks are usually tailored to be of intermediate difficulty, making it unnecessary.

Inter- and Intra-individual Variability in Strategy Use and Performance

The previous section reviewed a number of different strategies. Having a list of possible strategies is one thing, but one of the major reasons for researchers to be interested in strategies is their relation with performance: some strategies are typically more effective than others, leading to more accurate recall. This raises two inter-connected questions: among all possible strategies, which ones are most effective, and how does the use of these strategies vary across individuals?

In fact, most strategies seem to be relatively beneficial, with many studies finding a positive relation or, rarely, no relation between strategy use and performance. It may be the

case that without using strategies to scaffold encoding and maintenance of visuo-spatial stimuli, participants would be confined to passively waiting for recall while the visual memory trace rapidly declines (e.g. Fiore, Borella, Mammarella, & De Beni, 2012). The major exception to this positive view of strategies is verbal recoding, whose effectiveness has been frequently questioned in the literature; it has been shown that verbal recoding does not always improve performance, and can even impair recall (*verbal overshadowing* effect: see e.g. Brandimonte & Collina, 2008; for a different example, see Donkin, Nosofsky, Gold, & Shiffrin, 2015). This impairment could be due to interference between the verbal and visual memory traces at the time of recall (Brandimonte & Collina, 2008). However, this finding is not stable across studies, as multiple researchers have found that verbal recoding can indeed improve performance, sometimes to a greater extent than other strategies (Brown Nicholls & English, 2020; Kirchhoff & Buckner, 2006; Souza & Skóra, 2017).

Determining which strategies elicit the best performance is not quite straightforward. One reason is that the distribution of strategies is often very asymmetrical, with a few strategies appearing often and the rest relatively rarely (e.g. Kyllonen et al., 1984; Patt et al., 2014); another reason is that very few studies have directly tried to compare the effectiveness of different strategies. Overall, results are scattered and too inconsistent across studies to permit generalization; investigating the relative effects of various strategies on performance is certainly an open area for future research. To provide a few examples: visuo-spatial rehearsing has been found to improve performance, at least in older adults (Brown Nicholls & English, 2020; but see Lilienthal, Hale, & Myerson, 2016), but this is not always the case (Ridgeway, 2006). Counting up the number of targets has been described as an ineffective strategy, but it is not necessarily related to performance one way or another (Brown Nicholls & English, 2020; Ridgeway, 2006). Relational encoding of the targets in relation with each other may be beneficial (Kirchhoff & Bucker, 2006), as does memorizing distinctive features

of the display (Smith et al., 2010), and using semantic labeling (Brown Nicholls & English, 2020). Parsing a sequence of locations into several sub-sequences also improved performance in one study (Ridgeway, 2006). Keeping the gaze fixed in the center of the screen may also improve performance, even when stimuli are presented sequentially (Lange & Engbert, 2013).

Note that this largely positive view of strategies does not imply that they cannot have associated costs, which can especially appear as distortions at the time of recall. As mentioned above, memorizing stimuli in relation to a landmark distorts recall in the direction of the landmark (Hubbard & Ruppel, 2000); likewise, decomposing the reference frame into categorical locations such as quadrants shifts responses in the direction of prototypical locations (Huttenlocher et al., 1991; Huttenlocher et al., 2004; Starc et al., 2017). Encoding the position of a target relative to the closest edge of the reference frame means that it will be recalled with more precision in this direction than on the orthogonal axis (see Hartley et al., 2004, Figure 6). Stimuli that have been memorized as a chunk tend to be recalled in closer proximity than where they were actually located at encoding (Tversky, 2005; see also Dent & Smyth, 2006). Memorizing stimuli as a coherent chunk also means that the recall of the whole pattern can be completely incorrect if it is anchored on a misplaced target (see Newcombe, 1997; Schumann-Hengsteler et al., 2004). Chunking parts of a visual display can decrease complexity at encoding and facilitate visual processing, but it may also require enhanced relational encoding to properly memorize the relations between these chunks (Riby & Orme, 2013). Complex arrays of stimuli can be memorized as a unitary picture, but they rarely fit a perfect template exactly, and these discrepancies can be omitted at the time of recall (see Tversky, 2005, for an example where complex pictures tend to be recalled as if they were perfectly aligned along a vertical axis).

Another reason for the difficulty in identifying the most effective strategies is that subjects often use multiple strategies concurrently. In fact, one of the most consistent findings in the literature is that strategies in visuo-spatial STM tasks tend to vary frequently not only between individuals, but also between trials for the same individual (Kyllonen et al., 1984; Ridgeway, 2006; Strasser et al., 2010). Critically, subjects tend to perform visuo-spatial STM tasks better when they use multiple strategies (Brown & Wesley, 2013; Kirchoff, 2006; Smith et al., 2010; Strasser et al., 2010), indicating that knowing and making use of diverse strategies is beneficial. This use of multiple strategies does not just reflect random variation: instead, it seems to be the case that subjects flexibly adapt their strategy to the specific features of to-be-remembered stimuli (Kyllonen et al., 1984; Smith et al., 2010).

Both the spontaneous strategic variability across trials and the benefits of using multiple strategies have often been discussed for verbal STM tasks (e.g. Logie et al., 1996), and for spatial tasks other than memory tasks (such as mental rotation; Glück & Fitting, 2003; Glück et al., 2010; Hogeboom & van Leeuwen, 1997; Lajoie, 2013); these two points also find broad applicability in the context of visuo-spatial STM strategies. Indeed, most of the strategies reviewed here are intrinsically dependent on the specific organization of stimuli: for example, taking advantage of symmetry in the display, or ascribing meaning to a group of targets that has a particular shape reminiscent of a familiar object, or encoding the position of a target in relation to a proximal corner, all require a particular disposition of targets in the display. Such strategies could help performance in one trial but could be ineffective in another trial with a different configuration. In other words, another explanation for the difficulty in determining which strategies are most effective is that all strategies can be beneficial to an extent, but that their usefulness depends on affordances created by the features of a given trial, leading individuals to dynamically change their strategies within the task. Few researchers have been interested in this trial-to-trial variation; it may prove difficult to

investigate, if the strategies evoked by a trial are idiosyncratically contingent on the most salient features of the trial for a given individual. For example, one group of stimuli may evoke a meaningful chunk for one individual but not another.

This is not to say that there cannot be stable individual differences in visuo-spatial strategy use (for a discussion, see Lajoie, 2013; see also Glück & Fitting, 2003; Glück et al., 2010; Kirchoff & Buckner, 2006; Logie, 2011, 2018). Apart from personal preferences, individual abilities may orient participants towards one strategy (Kyllonen et al., 1984): for example, subjects with better verbal abilities may prefer to use verbal recoding, whereas individuals more skilled in the visuo-spatial domain could prefer purely visuo-spatial strategies. The study of Kyllonen and colleagues (1984) provided a few examples supporting this point: for example, subjects with higher mental visualization abilities seemed more prone to decompose complex figures into sub-parts at encoding, whereas subjects with lower visualization were more likely to use verbal recoding. Subjects may also differ in the breadth and diversity of their strategy repertoire, and in their ability to flexibly adapt their strategy use to features of the current trial, as has been found in other contexts (Kyllonen et al., 1984; Schunn & Reder, 1998, 2001). In sum, a likely conclusion is that visuo-spatial strategy use varies largely as a function of both item and individual (Kyllonen et al., 1984). More research is needed to ascertain this point, which remains largely unexplored in the particular context of visuo-spatial STM.

A Synthetic View of Strategy use in Visuo-Spatial Memory

The word "strategy" often evokes a particular picture in researchers: that of a subject choosing, more or less consciously, to approach a given task with a well-defined procedure which depends on the task. This procedure may be more or less effective, and the subject can be expected to stick to this procedure until the end of the task, barring an occasional change

of strategy. The data reviewed in the preceding sections make it clear that this simple picture does not apply very well to visuo-spatial STM tasks.

Strategies can be selected consciously, but they appear to be evoked, in part, by perceptual regularities in the display such as the presence of chunks or the possibility of semantic labeling. Strategies can be classified in broad categories, but a superficially simple strategy such as "chunking" or "verbal coding" can take many different forms (see Table 1), and there is some overlap between different types of strategies such as chunking, verbal recoding and semantic labeling. Strategies can vary across tasks, but the same strategy can be used across very different tasks, for sequential or simultaneous presentation of items, for meaningful objects or spatial locations, for structured or unstructured displays. Strategies can differ in terms of effectiveness, but most seem relatively beneficial under favorable circumstances, and most come with associated costs. Strategies can vary across individuals, but a given individual tends to use multiple strategies concurrently and to switch strategies across trials, presumably depending on the features of each trial.

Taken together, these conclusions point to a common picture of strategies as a library of broad facilitatory processes, on which subjects can draw to enhance performance in visuo-spatial STM tasks. In this sense, the groups listed in Table 1 can be viewed not as arbitrary categories of strategies, but as broad types of processes that can be used to support memory: essentially 1. chunking stimuli to decrease the number of separate pieces of information to remember, 2. making use of the overall layout or gist of the scene, 3. encoding the position of stimuli relative to other elements to support encoding of their spatial location, 4. grouping stimuli in categories to provide coarse positional information, 5. recoding stimuli to make use of cognitive systems other than visuo-spatial memory, 6. tapping into long-term memory, whether semantic or episodic, and 7. using visuo-spatial rehearsal to mentally refresh the memory trace. Which of these strategic processes are selected and how exactly they are

implemented depends on the perceptual organization of the to-be-memorized display in a given trial, and possibly on individual differences.

This view makes it clear that multiple strategies can be used within the same trial: subjects could make use of several facilitatory processes concurrently to support performance. For example, a set of targets could be memorized as a chunk forming a recognizable spatial configuration, with an associated semantic label; the position of this chunk could be encoded relative to the edge of the reference frame, and visuo-spatial rehearsal could be used during the retention period to mentally refresh the corresponding memory trace. This idea of multiple processes being used concurrently seems closer to the phenomenological reality of visuo-spatial STM tasks than a view of strategies as mutually exclusive, with subjects using either chunking or relational encoding or rehearsal: subjects may engage a single process (simple visuo-spatial rehearsal could be performed without any other strategy), or multiple processes.

This view also alleviates the problem of the overlap between different types of strategies (such as semantic labeling of chunks, subvocal rehearsal of verbal semantic labels, or visuo-spatial rehearsal of paths that constitute a meaningful holistic picture): different strategic processes may be reported separately in subjective reports and they might constitute partly distinct psychological phenomena, but they can be expected to co-occur frequently. Co-occurrence of strategies has not been systematically investigated in prior research (which has usually coded strategies at the trial level), and constitutes another possible direction for future studies.

All in all, the findings reviewed here appear to lead naturally to a view of strategies as discrete, non-exclusive implementations of a repertoire of facilitatory processes. Rather than "the way a subject performs the task", strategies can thus be viewed as "the ways a subject implements a range of cognitive processes that can support performance in the task". This

idea fits particularly well with a view of STM or working memory as "a dynamic process that emerges from a unified cognitive system flexibly adapting to the context and demands of each task" (Simmering & Perone, 2013; see also Arsalidou, 2013; Kovacs & Conway, 2016). In this sense, strategies can be considered as the behavioral manifestation of modular components of cognition being engaged to support performance in the task. Thus, carefully considering strategic behavior tends to support the recent trend, in short-term and working memory literature, of devoting more attention to the functional aspects of memory (which processes perform which functions in the service of recall; e.g. Engle & Kane, 2004) than to its structural aspects (how can the structure of memory be divided into a number of separate systems; e.g. Logie & Pearson, 1997).

Implications for Research and Practice

Variation Across Tasks and the Difference between Visual and Spatial Memory.

Visual memory (for static patterns of visual information) and spatial memory (for sequences of spatial positions) are often considered separately when discussing visuo-spatial STM. These two aspects of visuo-spatial memory correspond to different types of tasks (e.g. visual patterns task for visual memory, and Corsi blocks for spatial memory) and have been interpreted as two distinct components of a dedicated working memory system (the visual cache and inner scribe in Logie's framework; see Logie, 1995, 2011; Logie & Pearson, 1997). Due to this conceptual separation, one could expect the list of strategies to divide neatly into "strategies for visual material" (for stimuli presented simultaneously) and "strategies for spatial material" (for stimuli presented sequentially). For example, Lecerf and De Ribaupierre (2005) suggested that spatial locations presented sequentially can only be encoded as a path, not as a pattern.

The literature clearly indicates that this is not the case, and that there is significant overlap between the strategic processes used in visual and spatial tasks. As reviewed above, spatial locations presented sequentially can be chunked, and holistic encoding of the shape of the path between locations can occur; conversely, subjects report engaging in mental rehearsal (or refreshing) of static visual images, even though this strategy is usually associated with a sequential presentation. Verbal and kinesthetic recoding, relational encoding, and categorical encoding all occur for both types of tasks. In fact, none of the strategic processes reviewed here has been unequivocally described only for visual or spatial memory. From the angle of strategy use, the distinction between sequential and simultaneous seems to be a distinction between tasks as psychologists conceptualize them, more than between the processes they involve (see Logie, 2018).

Thus, considering strategy use in visuo-spatial STM logically leads to questioning the distinction between visual and spatial memory: many facilitatory processes used to scaffold aspects of encoding and rehearsal appear to be common to static visual material and sequences of spatial locations. Of course, this idea does not mean that visual and spatial tasks are interchangeable or that they tap into exactly the same components of cognition. This does not mean either that mode of presentation has no influence on strategy use: for example, a simultaneous presentation of to-be-remembered stimuli certainly makes chunking and semantic labeling easier, by making particular configurations of targets more conspicuous. What it does mean is that among the range of cognitive processes involved in visual and spatial STM tasks, there is significantly more overlap (Kovacs & Conway, 2016) than could be expected from the strict division often drawn in the literature between the two.

A related consequence of this idea is to draw attention on other features of the task that can contribute to strategy selection: indeed, other aspects of an experimental paradigm can influence strategy use, possibly to a greater extent than the simultaneous or sequential

mode of presentation. These differences across tasks may be random, or they may interact with individual differences; several studies have shown that the same subjects demonstrate little stability in their strategy use across tasks (Morrison et al., 2016; Logie, 2018). This is notably the case for verbal STM tasks that would appear to be highly similar but that differ in terms of the type of retrieval (free or serial recall, immediate or delayed recall, recall or recognition; Morrison et al., 2016). Thus, the type of retrieval, along with the instructions and context of encoding and with the type of materials can influence processing (see Roediger, 2008).

The literature suggests several parameters of visuo-spatial STM tasks that could strongly influence strategy use. One example is the degree to which configurations of targets are nameable: more recognizable configurations encourage the long-term-memory-based strategy of semantic labeling, enhancing performance (Brown et al., 2006). A second example is the choice between presenting the reference frame of spatial locations as structured (as a grid or matrix of locations) or unstructured (with a pseudo-random arrangement of locations, like the Corsi block-tapping task; see Figure 1b): an unstructured reference frame can discourage chunking (Bor et al., 2003), and presumably makes it harder to encode spatial positions in reference to edges of the reference frame. A third example is the duration of the interval between presentation of successive spatial locations, and the choice of displaying the empty reference frame or not during this interval, which can both influence implementation of visuo-spatial rehearsal (see Lilienthal et al., 2016). A final example is the role of complexity: highly complex trials can discourage the use of holistic strategies (Glück & Fitting, 2003) and instead encourage participants to decompose stimuli or sequences (Ridgeway, 2006); increasing the number of stimuli to remember can also promote chunking or holistic encoding (see Dent & Smyth, 2006).

Relations between Visuo-Spatial Short-Term Memory and Other Forms of Memory

Having noted the similarity between visual and spatial memory in terms of functional processes, a possible extension of the same idea is to question whether there is an absolute distinction between visuo-spatial memory and other memory systems. One argument for a close relationship between systems is that, as reviewed here, some strategies in visuo-spatial STM tap into episodic memory, semantic memory, and verbal memory. The overlap with long-term memory in particular is reminiscent of the view of STM as the subset of long-term memory that is currently activated (Cowan, 1999).

In the case of verbal STM, another argument comes from the observation that visuo-spatial strategies are involved in memorizing verbal materials, just like verbal recoding contributes to visuo-spatial STM. For instance, many studies in the field of dual coding have observed that words can be strategically recoded as mental images (Paivio 1991). This leads to the imageability of a word influencing recall performance (Paivio, 1969), and to visual interference impairing word recall (e.g. Quinn & McConnell, 1996, 2006). Other strategies used to memorize verbal materials do not constitute recoding as such but are still explicitly visuo-spatial in nature, such as the method of loci (wherein each to-be-remembered word is associated with a spatial location in a place the subject knows well; see e.g. Morey, 2018), and the encoding of words based on their visual shape when written (Logie, Saito, Morita, Varma, & Norris, 2016).

Materials such as Chinese and Japanese characters, which come with both visual and phonological representations for native speakers, demonstrate detrimental effects of both phonological and visual similarity, indicating that subjects use both visual and verbal coding (Lin, Chen, Lai, & Wu, 2015; Logie et al., 2016; Mou & Anderson, 1981; Saito, Logie, Morita, & Law, 2008). This dual coding depends on the context: for example, subjects tend to use more visual coding when the pronunciation of a given character is less well-known (Hue

& Erickson, 1988), indicating that they strategically select the most appropriate code (Logie et al., 2016). In other words, verbal and visual processes can evidently be integrated in the same task, for the same material.

Systematically comparing strategies for verbal and visuo-spatial STM tasks reveals a further layer of similarity. For instance, take a verbal serial recall task requiring subjects to memorize a series of words. Almost all strategies reviewed here are represented: these words can be grouped or chunked together; a sentence can be formed to link all words together, which can be viewed as a form of holistic encoding; and the words can be subdivided into categories (see e.g. Dunlosky & Kane, 2007). As mentioned above, words can be recoded, especially as pictures (Paivio, 1969, 1991). Tapping into long-term memory is frequent when memorizing words - semantic processing in particular is often discussed, and can be viewed as a strategy in that subjects can purposefully engage in semantic processing (see Rose, Myerson, Roediger, & Hale, 2010). Rehearsal of verbal materials has been described on innumerable occasions (e.g. Mora & Camos, 2013). Relational encoding may be the only strategic process that is not as readily applicable to a word list as it is to visuo-spatial material: strategies dealing with how to encode the spatial position of a target relative to other elements may not be as useful for a one-dimensional list of stimuli.

In short, the observation that similar functional processes are involved in both types of tasks suggests that verbal and visuo-spatial STM need not be viewed as rigidly separated systems. Some cognitive and neural components may be specifically dedicated to the processing of either type of materials (although whether visuo-spatial memory constitutes a truly separate memory store is debated; Morey, 2018), but the core set of strategic processes used to scaffold performance appears to be largely similar. Again, considering verbal and visuo-spatial STM under the light of strategy use encourages thinking in terms of partly overlapping functional processes (Kovacs & Conway, 2016). This is in line with frameworks

insisting on the shared role of processes such as executive attention (Engle & Kane, 2004) and maintenance of serial order (Majerus et al., 2010) for both types of tasks.

Interpreting Performance for Strategic Participants.

The diversity of visuo-spatial STM strategies, associated with significant variation across trials and individuals, makes it clear that not all subjects will do the same thing when asked to remember visuo-spatial material. This strategic variation may reflect meaningful individual differences in abilities and possibly in strategic adaptivity for researchers interested in this topic (e.g. Kyllonen et al., 1984), but it can also cause critical problems in other contexts, because different strategies represent different causal mechanisms of performance (Pearson & Keogh, 2019).

Four examples readily come to mind, as situations in which variability in strategies can elicit particular issues regarding the interpretation of performance: 1) studies interested in precise patterns of behavioral data, such as response times or spatial location of errors, because different strategies will reflect different processes and mechanisms, potentially biasing average patterns (Siegler, 1987); 2) studies interested in patterns of brain activity, because different processes will recruit different areas to different extents (Pearson & Keogh, 2019); 3) clinical psychologists and neuropsychologists interested in patient performance, for example in the context of deficits consecutive to a brain lesion, because strategies can constitute compensatory mechanisms masking the true extent of deficits; and 4) interpretation of differences of performance between individuals, which may reflect true individual differences of ability, or use of different strategies, or both (Logie, 2011).

All four examples are variations on the same idea: having a subject perform a visuo-spatial STM task does not tell us *how* the task is performed, and any measure can be misleading when it is unclear what process is involved. Take the example of brain activity,

which may be of particular interest given the increasing use of neuroimaging techniques (Pearson & Keogh, 2019). Storage of memory traces for different sensory modalities recruits different areas (Majerus et al., 2010), and different strategies can involve different sensory modalities. Subjects memorizing visual patterns may engage in verbal recoding, involving areas related to verbal processing and storage. In another condition (with different materials or a different sample), subjects may engage more kinesthetic processes and retrace the outline of patterns with their fingers, involving motor areas to a greater extent. A completely spurious difference of brain activity will then appear between the two conditions, when only strategy use truly differed. Conversely, from the point of view of clinical practice, a patient with a lesion in areas related to visuo-spatial processing may still demonstrate high performance if the task allows for verbal recoding, masking the true extent of the deficit.

The literature has particularly highlighted the importance of understanding strategies to interpret age-related differences in visuo-spatial STM (Brown Nicholls & English, 2020; Pearson & Keogh, 2019). Developmental studies on the progressive emergence of verbal recoding in children are well-known (Hitch et al., 1988, 1989; Logie & Pearson, 1997), but differences for knowledge-based strategies are also likely, given that older children have access to a wider knowledge base potentially allowing for easier semantic labeling of visual displays (Pickering, 2001). Visuo-spatial rehearsal can also vary across development (Pickering, 2001); one study found that children six years old and younger do not necessarily use visuo-spatial rehearsal, but that they demonstrate a benefit from meaningful configurations of stimuli consistent with a holistic strategy (Schumann-Hengsteler et al., 2004). Possible developmental differences in the use of landmarks and motor-based coding have also been discussed (see Newcombe, 1997). As for studies of normal aging, older adults seem to use less visuo-spatial rehearsal than younger adults for sequences of spatial locations, and possibly benefit less from this strategy (Fiore et al. 2012, Lilienthal et al. 2016).

Conversely, older adults may use less verbal or semantic recoding for visual patterns and rely more on visuo-spatial rehearsal than younger adults (Brown Nicholls & English 2013; see also Dai et al., 2018). Younger adults may also engage more easily in chunking than older adults (Dai et al., 2018).

These results illustrate that strategic differences could either confound, and/or meaningfully contribute to age-related differences in visuo-spatial STM, to the extent that the same task could be said to assess different functions at different ages (Johnson, Logie, & Brockmole, 2010; Logie, 2018). The same principle can apply to psychopathology: for example, variation in the use of a verbal recoding strategy has been claimed to account for STM differences between controls and patients with a bipolar disorder (Gallagher, Gray, & Kessels, 2015), and variation in the use of a holistic strategy has been observed in schizophrenia (Cocchi et al., 2009). Whether strategies are considered as a source of bias in the measurement of behavior, or as a meaningful contributor to individual differences in performance, will depend in part on whether they can be systematically related to stable individual traits, and in part on the particular focus of a given study. In both cases, the effect of strategy use on performance means that they should be taken into account to appropriately interpret findings.

There are two major ways to address the issue of strategy use. The first solution is to systematically consider possible variations in strategies when measuring visuo-spatial STM. This solution is clearly the best choice when strategic processes are viewed as a possibly meaningful contributor to differences between groups or individuals. Assessing strategies is not necessarily very difficult to achieve: for a coarse view of strategy use, end-of-task self-reports can be collected quickly and without being intrusive (for an example, see Patt et al., 2014). The second solution is to constrain strategy use so as to remove strategy-related variation and better pinpoint what processes the task recruits. There are at least two ways to

achieve this: 1) carefully selecting task parameters so as to decrease the use of certain strategies, such as verbal coding (Brown et al., 2006), rehearsal (Lilienthal et al., 2016), or chunking (Bor et al., 2003); and 2) explicitly instructing participants to use or avoid certain strategies (for examples in the verbal domain, see Logie et al., 1996; Turley-Ames & Whitfield, 2003). These two ways of constraining strategy use are complementary: some strategies may be difficult to prevent through manipulation of task parameters, whereas participants may not be able to voluntarily avoid using strategies, such as chunking, which are elicited relatively automatically by features of a trial.

Appropriately Assessing Strategy Use.

Studies of strategic behavior often infer strategy use based on eye-tracking or analysis of response patterns, or select experimental manipulations hypothesized to disrupt a given strategy. These methods are sometimes preferred based on the assumption that they are more "objective" than subjective self-reports, which are inherently suspect (Ericsson & Simon, 1980). This may indeed be true, when investigating a precise strategy associated with a tractable pattern of response times or eye movements. However, carefully reviewing the list of possible strategies indicates that certain strategies used in visuo-spatial STM tasks are inaccessible to this objective approach. Examples include kinesthetic strategies ("retracing the stimuli on one's leg"; Patt et al., 2014), and other strategies involving mental recoding ("making locations mentally correspond to audio tones"; Patt et al., 2014). By contrast, subjective verbal reports allow subjects to report on any and all strategies that are accessible to consciousness (Ericsson & Simon, 1980; see also Pearson & Keogh, 2019).

This leads to recommending verbal self-reports as the favored method for researchers interested in assessing the diversity of strategies used by their subjects. To control for methodological biases (for discussions, see Ericsson & Simon, 1980; Fox, Ericsson, & Best,

2011; Richardson, 1998), such as strategy reports interfering with spontaneous strategy use, it may be desirable to vary the way strategy reports are implemented across experiments (e.g., forced-choice or free verbal report; see Dunlosky & Kane, 2007). Given the variations of visuo-spatial strategies for the same individual across trials of the same task, it is clearly unwarranted to treat strategy as a stable individual trait (Glück, 2003), which means trial-to-trial self-reports should be favored and end-of-task self-reports avoided by researchers and psychologists dedicated to investigating strategy use precisely (see also Ridgeway, 2006). However, it is probably best to avoid having subjects verbalize concurrently with the trial: given that the task content is not intrinsically verbal, there is a high likelihood of reactive effects (verbalization interfering with performance; Ericsson & Simon, 1980; Fox et al., 2011).

Another important point that emerges from this review is the existence of gradients of subtly different strategies, which may be easily confused with one another when using coarse verbal reports. One example is "chunking" strategies, where chunks can be constituted due to simple proximity (e.g. Woodman et al., 2003), or because the group of locations resembles a geometric shape (e.g. Dai et al., 2018), or a meaningful object such as a letter (e.g. Brown et al., 2006). These types of chunks imply different degrees of nameability and different uses of verbal and semantic processes. Likewise, "verbal coding" strategies range from constructing sentences that describe the display (Kirchhoff & Buckner 2006) to counting the number of stimuli (e.g. Brown Nicholls & English, 2020) through using elaborate coordinate systems (Strasser et al., 2010). Precision is thus required in collecting self-reports to understand the precise strategy used by a subject.

A related issue is the moment when a particular strategy takes place. This is especially ambiguous for visuo-spatial rehearsal (Ridgeway, 2006): subjects can use attention-based rehearsal of visuo-spatial stimuli (sometimes by rehearsing a path between targets), but this

"rehearsal" can take place either during encoding, during the retention interval, or both. Subjects tend to rehearse during encoding and during retention to different extents (e.g. 33% vs. 62% of trials, respectively; Ridgeway, 2006), and the two may have slightly different impacts on performance (Ridgeway, 2006). When exactly a strategy is implemented has consequences for the interpretation of patterns of brain activity and eye movements (e.g. Guérard et al., 2009), and should be taken into account for a fine-grained analysis of strategy use.

Of course, using verbal reports does not preclude analyzing non-subjective indices such as eye movements or response patterns. Verbal reports have well-known limitations, especially when they are not performed concurrently with the task (Ericsson & Simon, 1980). One of them is that they involve reconstruction of past experience, which may not be quite reliable, especially for strategies that are not selected consciously during the task. Given the nature of some visuo-spatial strategies, another possible issue in the present case is under-reporting of strategies that are not identified as such by the subjects themselves: for example, subjects may fail to consider "retracing stimuli with one's fingers" as a strategy they should mention to the experimenter. The latter issue can be mitigated by providing subjects with a forced-choice list of strategies to choose from, but this can in turn influence strategy use on subsequent trials. Researchers interested in assessing the use of a specific strategy should consider collecting additional data (such as electromyographic data for kinesthetic strategies) and/or studying response patterns to search for distortions associated with certain strategies (see above). However, this would be impractical for researchers aiming to cover the whole range of strategies reported in Table 1: in this case, verbal reports would be difficult to replace.

Limitations and Outstanding Issues.

As reflected in this review, strategies for visuo-spatial STM have not been consistently studied and evidence is highly scattered. Most researchers who have discussed procedures underlying performance have not used a consistent keyword such as "strategy", adding to this complexity. The current synthesis is certainly not definitive, but visuo-spatial STM has been studied enough that all major aspects of strategy use have probably appeared in published literature. For this reason, the list of strategic processes presented in Table 1 should be relatively exhaustive. Details of how these processes are implemented in a given paradigm may vary, however, and there can be variations that are not listed here.

A recurring issue is the extent to which a given process is strategic, especially when it is driven by affordances of the task rather than conscious selection. This is the case for many strategies listed here, such as chunking stimuli that are close or symmetrical, or semantic labeling of meaningful configurations. On the other hand, the same procedures are usually considered as strategic in the context of verbal STM tasks; besides, strategy selection is driven by task features and proceeds without any conscious awareness in many domains (for a review, see Cary & Reder, 2002). This issue may ultimately come down to the fact that strategic and non-strategic processes exist on a continuum, without an absolute distinction between the two: there are functional processes that are implemented to support encoding and maintenance, and these processes are under varying levels of conscious monitoring and regulation. The criteria used for the current review (of a process being strategic as long as it can be brought to consciousness and is not a mandatory part of the task) were based on this idea.

Another recurring issue is the grouping in Table 1 of different strategies as being variations of the same process (such as symmetry-based and proximity-based chunking) and, conversely, the division of overlapping strategies in separate processes (such as chunking and semantic labeling, when in fact semantic labeling tends to operate on chunks of targets).

Again, this may be an issue of arbitrary definition: functional processes are classified in arbitrary categories for our understanding but are seamlessly integrated in cognition. Contrary to the definition of strategies, however, this is an area that can be fruitfully explored in future research: based on patterns of behavior (such as response times, order of recall, and distortions at recall) or brain activity, it should be possible to refine our understanding of the degree to which different strategies constitute similar or separate processes. As mentioned, grouping strategies in the major processes listed in Table 1 was partly arbitrary and partly based on conceptual similarity, not always on precise insight into behavioral or neural signatures.

Apart from the boundaries between strategies, the weaker point of the current review is clearly the question of how strategies affect performance, and what determines strategy selection. There is enough evidence to know that strategies are not all equally effective, and that using multiple strategies is beneficial, but differences of experimental paradigms between studies confound differences of strategies, and make it difficult to draw more definitive conclusions. This question is simultaneously the most relevant to the interpretation of differences between tasks and between individuals, and the one least systematically explored in past research. My conviction is that the major obstacle to progress in this area has been the lack of an integrative taxonomy of strategies in visuo-spatial STM, and I hope the synthesis provided here can help further progress on this topic by serving as a conceptual framework.

Conclusion

The literature points to a large diversity of strategic processes used in visuo-spatial memory tasks, with considerable overlap between strategies used for static visual material and sequences of spatial locations. These strategic processes can be broadly classified in

seven types: chunking, holistic encoding, relational encoding, categorical encoding, mental recoding, making use of long-term semantic or episodic memory, and visuo-spatial rehearsal. It seems that these processes can be used concurrently, and that the precise way they are implemented, their use and their effectiveness depend on features of the to-be-remembered display and on individual differences. These aspects of strategy use point to a view of visuo-spatial memory as a performance emerging dynamically from a set of partly overlapping cognitive processes, which operate together. Given that different strategies can be associated with different levels of performance, and with different patterns of behavior and brain activity, strategy use should be systematically taken into account by clinicians and researchers interested in the causal mechanisms of performance, preferably incorporating trial-level subjective self-reports.

References

- Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2014). Evidence for two attentional components in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 40(6), 1499–1509. doi:10.1037/xlm0000002
- Arsalidou, M. (2013). Working memory capacity: The need for process task-analysis. *Frontiers in Psychology*, 4. doi:10.3389/fpsyg.2013.00257
- Avons, S. E. (2007). Spatial span under translation: A study of reference frames. *Memory & Cognition*, 35(3), 402–417. doi:10.3758/BF03193281
- Avons, S. E., & Phillips, W. A. (1987). Representation of matrix patterns in long- and short-term visual memory. *Acta Psychologica*, 65(3), 227–246. doi:10.1016/0001-6918(87)90051-5
- Awh, E., Anllo-Vento, L., & Hillyard, S. A. (2000). The role of spatial selective attention in working memory for locations: Evidence from event-related potentials. *Journal of Cognitive Neuroscience*, 12(5), 840–847. doi:10.1162/089892900562444
- Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, 5(3), 119–126. doi:10.1016/S1364-6613(00)01593-X
- Bennett-Levy, J. (1984). Determinants of performance on the Rey–Osterrieth Complex Figure Test: An analysis, and a new technique for single-case assessment. *British Journal of Clinical Psychology*, 23(2), 109–119. doi:10.1111/j.2044-8260.1984.tb00634.x
- Berger, G. H., & Gaunitz, S. C. (1979). Self-rated imagery and encoding strategies in visual memory. *British Journal of Psychology*, 70(1), 21–24. doi:10.1111/j.2044-8295.1979.tb02137.x
- Blalock, L. D., & Clegg, B. A. (2010). Encoding and representation of simultaneous and sequential arrays in visuospatial working memory. *The Quarterly Journal of Experimental Psychology*, 63(5), 856–862. doi:10.1080/17470211003690680
- Bor, D., Duncan, J., & Owen, A. M. (2001). The role of spatial configuration in tests of working memory explored with functional neuroimaging. *Scandinavian Journal of Psychology*, 42(3), 217–224. doi:10.1111/1467-9450.00232
- Bornstein, M. H., & Stiles-Davis, J. (1984). Discrimination and memory for symmetry in young children. *Developmental Psychology*, 20(4), 637–649. doi:10.1037/0012-1649.20.4.637
- Brady, T. F., Konkle, T., & Alvarez, G. A. (2009). Compression in visual working memory: Using statistical regularities to form more efficient memory representations. *Journal of Experimental Psychology: General*, 138(4), 487–502. doi:10.1037/a0016797

- Brandimonte, M. A., & Collina, S. (2008). Verbal overshadowing in visual imagery is due to recoding interference. *European Journal of Cognitive Psychology*, 20(3), 612–631. doi:10.1080/09541440701728441
- Brown, L. A., & Wesley, R. W. (2013). Visual working memory is enhanced by mixed strategy use and semantic coding. *Journal of Cognitive Psychology*, 25(3), 328–338. doi:10.1080/20445911.2013.773004
- Brown, L. A., Forbes, D., & McConnell, J. (2006). Limiting the use of verbal coding in the Visual Patterns Test. *The Quarterly Journal of Experimental Psychology*, 59(7), 1169–1176. doi:10.1080/17470210600665954
- Brown Nicholls, L. A., & English, B. (2020). Multimodal coding and strategic approach in young and older adults' visual working memory performance. *Aging, Neuropsychology, and Cognition*, 27(1), 83–113. doi:10.1080/13825585.2019.1585515
- Bruyer, R., Scailquin, J.-C., & Coibion, P. (1997). Dissociation between categorical and coordinate spatial computations: Modulation by cerebral hemispheres, task properties, mode of response, and age. *Brain and Cognition*, 33(3), 245–277. doi:10.1006/brcg.1997.0867
- Cary, M., & Reder, L. M. (2002). Metacognition in strategy selection. In P. Chambres, M. Izaute, & P.-J. Marescaux (Eds.), *Metacognition: Process, function and use*. (pp. 63–77). Kluwer Academic Publishers. doi:10.1007/978-1-4615-1099-4_5
- Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology*, 4(1), 55–81. doi:10.1016/0010-0285(73)90004-2
- Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology*, 36(1), 28–71. doi:10.1006/cogp.1998.0681
- Clevenger, P. E., & Hummel, J. E. (2014). Working memory for relations among objects. *Attention, Perception, & Psychophysics*, 76(7), 1933–1953. doi:10.3758/s13414-013-0601-3
- Cocchi, L., Bosisio, F., Berchtold, A., Orita, A., Debbané, M., Wood, S. J., & Schenk, F. (2009). Visuospatial encoding deficits and compensatory strategies in schizophrenia revealed by eye movement analysis during a working memory task. *Acta Neuropsychiatrica*, 21(2), 75–83. doi:10.1111/j.1601-5215.2009.00369.x
- Corsi, P. M. (1973). Human memory and the medial temporal region of the brain. In *Dissertation Abstracts International* (Vol. 34, Issue 2–B, p. 891).
- Cowan, N. (1999). An Embedded-Processes Model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (p. 62–101). Cambridge University Press. doi:10.1017/CBO9781139174909.006

- Czoschke, S., Henschke, S., & Lange, E. B. (2019). On-item fixations during serial encoding do not affect spatial working memory. *Attention, Perception, & Psychophysics*, 81, 2766–2787. doi:10.3758/s13414-019-01786-5
- Dai, R., Thomas, A. K., & Taylor, H. A. (2018). Age-related differences in the use of spatial and categorical relationships in a visuo-spatial working memory task. *Memory & Cognition*, 46(5), 809–825. <https://doi-org.distant.bu.univ-rennes2.fr/10.3758/s13421-018-0794-8>
- Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwinding visuo-spatial memory. *Neuropsychologia*, 37(10), 1189–1199. doi:10.1016/S0028-3932(98)00159-6
- Delvenne, J.-F., & Bruyer, R. (2006). A configural effect in visual short-term memory for features from different parts of an object. *The Quarterly Journal of Experimental Psychology*, 59(9), 1567–1580. doi:10.1080/17470210500256763
- Dent, K., & Smyth, M. M. (2006). Capacity limitations and representational shifts in spatial short-term memory. *Visual Cognition*, 13(5), 529–572. doi:10.1080/13506280444000760
- Donkin, C., Nosofsky, R., Gold, J., & Shiffrin, R. (2015). Verbal labeling, gradual decay, and sudden death in visual short-term memory. *Psychonomic Bulletin & Review*, 22(1), 170–178. doi:10.3758/s13423-014-0675-5
- Dunlosky, J., & Kane, M. J. (2007). The contributions of strategy use to working memory span: A comparison of strategy assessment methods. *The Quarterly Journal of Experimental Psychology*, 60(9), 1227–1245. doi:10.1080/17470210600926075
- Engle, R. W., & Kane, M. J. (2004). Executive Attention, Working Memory Capacity, and a Two-Factor Theory of Cognitive Control. In B. H. Ross (Ed.), *The psychology of learning and motivation: Advances in research and theory*, Vol. 44 (pp. 145–199). Elsevier Science.
- Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review*, 87(3), 215–251. doi:10.1037/0033-295X.87.3.215
- Faw, B. (2003). Pre-frontal executive committee for perception, working memory, attention, long-term memory, motor control, and thinking: A tutorial review. *Consciousness and Cognition*, 12(1), 83–139. doi:10.1016/S1053-8100(02)00030-2
- Fiore, F., Borella, E., Mammarella, I. C., & De Beni, R. (2012). Age differences in verbal and visuo-spatial working memory updating: Evidence from analysis of serial position curves. *Memory*, 20(1), 14–27. doi:10.1080/09658211.2011.628320
- Fox, M. C., Ericsson, K. A., & Best, R. (2011). Do procedures for verbal reporting of thinking have to be reactive? A meta-analysis and recommendations for best reporting methods. *Psychological Bulletin*, 137(2), 316–344. doi:10.1037/a0021663

- Gallagher, P., Gray, J. M., & Kessels, R. P. C. (2015). Fractionation of visuo-spatial memory processes in bipolar depression: A cognitive scaffolding account. *Psychological Medicine*, 45(3), 545–558. doi:10.1017/S0033291714001676
- Glück, J., & Fitting, S. (2003). Spatial strategy selection: Interesting incremental information. *International Journal of Testing*, 3(3), 293–308. doi:10.1207/S15327574IJT0303_7
- Glück, J., Quaiser-Pohl, C., & Neubauer, A. C. (2010). New approaches to studying individual differences in spatial abilities. *Journal of Individual Differences*, 31(2), 57–58. doi:10.1027/1614-0001/a000025
- Gmeindl, L., Nelson, J. K., Wiggin, T., & Reuter-Lorenz, P. A. (2011). Configural representations in spatial working memory: Modulation by perceptual segregation and voluntary attention. *Attention, Perception, & Psychophysics*, 73(7), 2130–2142. doi:10.3758/s13414-011-0180-0
- Godijn, R., & Theeuwes, J. (2012). Overt is no better than covert when rehearsing visuo-spatial information in working memory. *Memory & Cognition*, 40(1), 52–61. doi:10.3758/s13421-011-0132-x
- Gonthier, C., & Roulin, J.-L. (2019). Intraindividual strategy shifts in Raven's matrices, and their dependence on working memory capacity and need for cognition. *Journal of Experimental Psychology: General*. doi:10.1037/xge0000660
- Guérard, K., Tremblay, S., & Saint-Aubin, J. (2009). The processing of spatial information in short-term memory: Insights from eye tracking the path length effect. *Acta Psychologica*, 132(2), 136–144. doi:10.1016/j.actpsy.2009.01.003
- Guérard, K., & Tremblay, S. (2012). The effect of path length and display size on memory for spatial information. *Experimental Psychology*, 59(3), 147–152. doi:10.1027/1618-3169/a000137
- Hartley, T., Trinkler, I., & Burgess, N. (2004). Geometric determinants of human spatial memory. *Cognition*, 94(1), 39–75. doi:10.1016/j.cognition.2003.12.001
- Hellige, J. B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing spatial information. *Memory & Cognition*, 17(6), 770–776. doi:10.3758/BF03202638
- Hitch, G. J., Brandimonte, M. A., & Walker, P. (1995). Two types of representation in visual memory: Evidence from the effects of stimulus contrast on image combination. *Memory & Cognition*, 23(2), 147–154. doi:10.3758/BF03197217
- Hitch, G. J., Halliday, M. S., Dodd, A., & Littler, J. E. (1989). Development of rehearsal in short-term memory: Differences between pictorial and spoken stimuli. *British Journal of Developmental Psychology*, 7(4), 347–362. doi:10.1111/j.2044-835X.1989.tb00811.x

- Hitch, G. J., Halliday, S., Schaafstal, A. M., & Schraagen, J. M. (1988). Visual working memory in young children. *Memory & Cognition*, 16(2), 120–132. doi:10.3758/BF03213479
- Hogeboom, M., & van Leeuwen, C. (1997). Visual search strategy and perceptual organization covary with individual preference and structural complexity. *Acta Psychologica*, 95(2), 141–164. doi:10.1016/S0001-6918(96)00049-2
- Hollingworth, A. (2007). Object-position binding in visual memory for natural scenes and object arrays. *Journal of Experimental Psychology: Human Perception and Performance*, 33(1), 31–47. doi:10.1037/0096-1523.33.1.31
- Howe, E., & Jung, K. (1986). Immediate memory span for two-dimensional spatial arrays: Effects of pattern symmetry and goodness. *Acta Psychologica*, 61(1), 37–51. doi:10.1016/0001-6918(86)90020-X
- Hu, Y., Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2016). Executive control of stimulus-driven and goal-directed attention in visual working memory. *Attention, Perception, & Psychophysics*, 78(7), 2164–2175. doi:10.3758/s13414-016-1106-7
- Hubbard, T. L., & Ruppel, S. E. (2000). Spatial memory averaging, the landmark attraction effect, and representational gravity. *Psychological Research*, 64(1), 41–55. doi:10.1007/s004260000029
- Hue, C., & Erickson, J. R. (1988). Short-term memory for Chinese characters and radicals. *Memory & Cognition*, 16(3), 196–205. doi:10.3758/BF03197752
- Huttenlocher, J., Hedges, L. V., & Duncan, S. (1991). Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review*, 98(3), 352–376. doi:10.1037/0033-295X.98.3.352
- Huttenlocher, J., Hedges, L. V., Corrigan, B., & Crawford, L. E. (2004). Spatial categories and the estimation of location. *Cognition*, 93(2), 75–97. doi:10.1016/j.cognition.2003.10.006
- Ikkai, A., & Curtis, C. E. (2011). Common neural mechanisms supporting spatial working memory, attention and motor intention. *Neuropsychologia*, 49(6), 1428–1434. doi:10.1016/j.neuropsychologia.2010.12.020
- Imbo, I., Szmalec, A., & Vandierendonck, A. (2009). The role of structure in age-related increases in visuo-spatial working memory span. *Psychologica Belgica*, 49(4), 275–291. doi:10.5334/pb-49-4-275
- Jiang, Y., Chun, M. M., & Olson, I. R. (2004). Perceptual grouping in change detection. *Perception & Psychophysics*, 66(3), 446–453. doi:10.3758/BF03194892
- Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26(3), 683–702. doi:10.1037/0278-7393.26.3.683

- Johnson, W., Logie, R.H. & Brockmole, J.R. (2010). Working memory tasks differ in factor structure across age cohorts: Implications for differentiation. *Intelligence*, 38, 513–528. doi:10.1016/j.intell.2010.06.005
- Jones, D. M., Hughes, R. W., & Macken, W. J. (2006). Perceptual organization masquerading as phonological storage: Further support for a perceptual-gestural view of short-term memory. *Journal of Memory and Language*, 54(2), 265–281. doi:10.1016/j.jml.2005.10.006
- Kemps, E. (1999). Effects of complexity on visuo-spatial working memory. *European Journal of Cognitive Psychology*, 11(3), 335–356. doi:10.1080/713752320
- Kemps, E. (2001). Complexity effects in visuo-spatial working memory: Implications for the role of long-term memory. *Memory*, 9(1), 13–27. doi:10.1080/09658210042000012
- 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. doi:10.1207/S15324826AN0704_8
- Kirchhoff, B. A., & Buckner, R. L. (2006). Functional-anatomic correlates of individual differences in memory. *Neuron*, 51, 263–274. doi:10.1016/j.neuron.2006.06.006
- Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review*, 94(2), 148–175. doi:10.1037/0033-295X.94.2.148
- Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. E. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Performance*, 15(4), 723–735. doi:10.1037/0096-1523.15.4.723
- Kovacs, K., & Conway, A. R. A. (2016) Process Overlap Theory: A unified account of the general factor of intelligence. *Psychological Inquiry*, 27(3), 151–177. doi:10.1080/1047840X.2016.1153946
- Kyllonen, P. C., Lohman, D. F., & Woltz, D. J. (1984). Componential modeling of alternative strategies for performing spatial tasks. *Journal of Educational Psychology*, 76(6), 1325–1345. doi:10.1037/0022-0663.76.6.1325
- Lajoie, S. P. (2003). Individual differences in spatial ability: Developing technologies to increase strategy awareness and skills. *Educational Psychologist*, 38(2), 115–125. doi:10.1207/S15326985EP3802_6
- Lane, D. M., & Chang, Y.-H. A. (2018). Chess knowledge predicts chess memory even after controlling for chess experience: Evidence for the role of high-level processes. *Memory & Cognition*, 46(3), 337–348. doi:10.3758/s13421-017-0768-2
- Lange, E. B., & Engbert, R. (2013). Differentiating between verbal and spatial encoding using eye-movement recordings. *The Quarterly Journal of Experimental Psychology*, 66(9), 1840–1857. doi:10.1080/17470218.2013.772214

- Lecerf, T., & de Ribaupierre, A. (2005). Recognition in a visuospatial memory task: The effect of presentation. *European Journal of Cognitive Psychology*, 17(1), 47–75. doi:10.1080/09541440340000420
- Lemaire, P., & Reder, L. (1999). What affects strategy selection in arithmetic? The example of parity and five effects on product verification. *Memory & Cognition*, 27(2), 364–382. doi:10.3758/BF03211420
- Liao, D. A., Kronemer, S. I., Yau, J. M., Desmond, J. E., & Marvel, C. L. (2014). Motor system contributions to verbal and non-verbal working memory. *Frontiers in Human Neuroscience*, 8. doi:10.3389/fnhum.2014.00753
- Lilienthal, L., Hale, S., & Myerson, J. (2016). Effects of age and environmental support for rehearsal on visuospatial working memory. *Psychology and Aging*, 31(3), 249–254. doi:10.1037/pag0000077
- Lin, Y.-C., Chen, H.-Y., Lai, Y. C., & Wu, D. H. (2015). Phonological similarity and orthographic similarity affect probed serial recall of Chinese characters. *Memory & Cognition*, 43(3), 538–554. doi:10.3758/s13421-014-0495-x
- Logie, R. H. (1995). *Visuo-spatial working memory*. Hillsdale, NJ, US: Lawrence Erlbaum Associates, Inc.
- Logie, R. H. (2011). The functional organization and capacity limits of working memory. *Current Directions in Psychological Science*, 20(4), 240–245. doi:10.1177/0963721411415340
- Logie, R. (2018). Human cognition: Common principles and individual variation. *Journal of Applied Research in Memory and Cognition*, 7(4), 471–486. doi:10.1016/j.jarmac.2018.08.001
- Logie, R. H., & Marchetti, C. (1991). Visuo-spatial working memory: Visual, spatial or central executive? In R. H. Logie & M. Denis (Eds.), *Mental images in human cognition* (pp. 105–115). Oxford, UK: North-Holland. doi:10.1016/S0166-4115(08)60507-5
- Logie, R. H., & Pearson, D. G. (1997). The inner eye and the inner scribe of visuo-spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology*, 9(3), 241–257. doi:10.1080/713752559
- Logie, R. H., Saito, S., Morita, A., Varma, S., & Norris, D. (2016). Recalling visual serial order for verbal sequences. *Memory & Cognition*, 44(4), 590–607. doi:10.3758/s13421-015-0580-9
- Magen, H., & Berger-Mandelbaum, A. (2018). Encoding strategies in self-initiated visual working memory. *Memory & Cognition*, 46(7), 1093–1108. doi:10.3758/s13421-018-0823-7
- Majerus, S., D'Argembeau, A., Perez, T. M., Belayachi, S., Van der Linden, M., Collette, F., Salmon, E., Seurinck, R., Fias, W., & Maquet, P. (2010). The commonality of neural

- networks for verbal and visual short-term memory. *Journal of Cognitive Neuroscience*, 22(11), 2570–2593. doi:10.1162/jocn.2009.21378
- Majerus, S. (2013). Language repetition and short-term memory: an integrative framework. *Frontiers in Human Neuroscience*, 7. doi:10.3389/fnhum.2013.00357
- Meiser, T., & Klauer, K. C. (1999). Working memory and changing-state hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25(5), 1272–1299. doi:10.1037/0278-7393.25.5.1272
- Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, 63(2), 81–97. doi:10.1037/h0043158
- 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. doi:10.1037/0096-3445.130.4.621
- Mora, G., & Camos, V. (2013). Two systems of maintenance in verbal working memory: evidence from the word length effect. *PLoS One*, 8(7):e70026. doi:10.1371/journal.pone.0070026
- Morey, C. C. (2018). The case against specialized visual-spatial short-term memory. *Psychological Bulletin*, 144(8), 849–883. doi:10.1037/bul0000155
- Morey, C. C. (2019). Perceptual grouping boosts visual working memory capacity and reduces effort during retention. *British Journal of Psychology*, 110, 306–327. doi:10.1111/bjop.12355
- Morey, C. C., Cong, Y., Zheng, Y., Price, M., & Morey, R. D. (2015). The color-sharing bonus: Roles of perceptual organization and attentive processes in visual working memory. *Archives of Scientific Psychology*, 3(1), 18–29. doi:10.1037/arc0000014
- Morrison, A. B., Rosenbaum, G. M., Fair, D., & Chein, J. M. (2016). Variation in strategy use across measures of verbal working memory. *Memory & Cognition*, 44(6), 922–936. doi:10.3758/s13421-016-0608-9
- Mou, L. C., & Anderson, N. S. (1981). Graphemic and phonemic codings of Chinese characters in short-term retention. *Bulletin of the Psychonomic Society*, 17, 255 – 258. doi:10.3758/BF03333732
- Newcombe, N. S. (1997). New perspectives on spatial representation: What different tasks tell us about how people remember location. In N. Foreman and R. Gillett (Eds.), *A handbook of spatial research paradigms and methodologies* (pp. 85-102). East Sussex, UK: Psychology Press, Taylor and Francis Group.
- Newcombe, N. S., & Huttenlocher, J. (2007). Development of Spatial Cognition. In D. Kuhn, R. S. Siegler, W. Damon, & R. M. Lerner (Eds.), *Handbook of child psychology*:

Cognition, perception, and language, Vol. 2, 6th ed. (pp. 734–776). Hoboken, NJ, US: John Wiley & Sons Inc.

- Noton, D., & Stark, L. (1971). Scanpaths in saccadic eye movements while viewing and recognizing patterns. *Vision Research*, 11(9), 929–942. doi:10.1016/0042-6989(71)90213-6
- Orbán, G., Fiser, J., Aslin, R. N., & Lengyel, M. (2008). Bayesian learning of visual chunks by human observers. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, 105(7), 2745–2750. doi:10.1073/pnas.0708424105
- Paivio, A. (1969). Mental imagery in associative learning and memory. *Psychological Review*, 76(3), 241–263. doi:10.1037/h0027272
- Paivio, A. (1991). Dual coding theory: retrospect and current status. *Canadian Journal of Psychology*, 45(3), 255–287. doi:10.1037/h0084295
- Parmentier, F. B. R., Elford, G., & Maybery, M. (2005). Transitional Information in Spatial Serial Memory: Path Characteristics Affect Recall Performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 31(3), 412–427. doi:10.1037/0278-7393.31.3.412
- Patt, V. M., Thomas, M. L., Minassian, A., Geyer, M. A., Brown, G. G., & Perry, W. (2014). Disentangling working memory processes during spatial span assessment: A modeling analysis of preferred eye movement strategies. *Journal of Clinical and Experimental Neuropsychology*, 36(2), 186–204. doi:10.1080/13803395.2013.877123
- Pearson, D. G., Ball, K., & Smith, D. T. (2014). Oculomotor preparation as a rehearsal mechanism in spatial working memory. *Cognition*, 132(3), 416–428. doi:10.1016/j.cognition.2014.05.006
- Pearson, D. G., & Sahraie, A. (2003). Oculomotor control and the maintenance of spatially and temporally distributed events in visuo-spatial working memory. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology*, 56A(7), 1089–1111. doi:10.1080/02724980343000044
- Pearson, J., & Keogh, R. (2019). Redefining visual working memory: A cognitive-strategy, brain-region approach. *Current Directions in Psychological Science*, 28(3), 266–273. doi:10.1177/0963721419835210
- Peterson, D. J., & Berryhill, M. E. (2013). The Gestalt principle of similarity benefits visual working memory. *Psychonomic Bulletin & Review*, 20(6), 1282–1289. doi:10.3758/s13423-013-0460-x
- Pickering, S. J. (2001). The development of visuo-spatial working memory. *Memory*, 9(4–6), 423–432. doi:10.1080/09658210143000182
- Postma, A., Kessels, R. P. C., & van Asselen, M. (2004). The Neuropsychology of Object-Location Memory. In G. L. Allen (Ed.), *Human spatial memory: Remembering where*. (pp. 143–160). Lawrence Erlbaum Associates Publishers.

- Postma, A., Kessels, R. P. C., & van Asselen, M. (2008). How the brain remembers and forgets where things are: The neurocognition of object-location memory. *Neuroscience and Biobehavioral Reviews*, 32(8), 1339–1345. doi:10.1016/j.neubiorev.2008.05.001
- Quinn, J. G., & Ralston, G. E. (1986). Movement and attention in visual working memory. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology*, 38(4-A), 689–703. doi:10.1080/14640748608401621
- Quinn, J. G., & McConnell, J. (1996). Irrelevant pictures in visual working memory. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology*, 49, 200–215. doi:10.1080/713755613
- Quinn, J. G., & McConnell, J. (2006). The interval for interference in conscious visual imagery. *Memory*, 14, 241–252. doi:10.1080/09658210500210019
- Rashal, E., Yeshurun, Y., & Kimchi, R. (2017). Attentional requirements in perceptual grouping depend on the processes involved in the organization. *Attention, Perception, & Psychophysics*, 79(7), 2073–2087. doi:10.3758/s13414-017-1365-y
- Rensink, R. A. (2000). The dynamic representation of scenes. *Visual Cognition*, 7(1–3), 17–42. doi:10.1080/135062800394667
- Riby, L. M., & Orme, E. (2013). A familiar pattern? Semantic memory contributes to the enhancement of visuo-spatial memories. *Brain and Cognition*, 81(2), 215–222. <https://doi-org.distant.bu.univ-rennes2.fr/10.1016/j.bandc.2012.10.011>
- Richardson, J. T. E. (1998). The availability and effectiveness of reported mediators in associative learning: A historical review and an experimental investigation. *Psychonomic Bulletin & Review*, 5(4), 597–614. doi:10.3758/BF03208837
- Ridgeway, D. (2006). Strategic grouping in the spatial span memory task. *Memory*, 14(8), 990–1000. doi:10.1080/09658210601010797
- Roediger, H. L., III. (2008). Relativity of remembering: Why the laws of memory vanished. *Annual Review of Psychology*, 59, 225–254. doi:10.1146/annurev.psych.57.102904.190139
- Rose, N. S., Myerson, J., Roediger, H. L., III, & Hale, S. (2010). Similarities and differences between working memory and long-term memory: Evidence from the levels-of-processing span task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36(2), 471–483. doi:10.1037/a0018405
- Rosenbloom, M. J., Sasso, S. A., Pfefferbaum, A., & Sullivan, E. V. (2009). Contribution of regional White matter integrity to visuospatial construction accuracy, organizational strategy, and memory for a complex figure in abstinent alcoholics. *Brain Imaging and Behavior*, 3(4), 379–390. doi:10.1007/s11682-009-9080-5
- Rossi-Arnaud, C., Pieroni, L., & Baddeley, A. (2006). Symmetry and binding in visuo-spatial working memory. *Neuroscience*, 139(1), 393–400. doi:10.1016/j.neuroscience.2005.10.048

- Rossi-Arnaud, C., Pieroni, L., Spataro, P., & Baddeley, A. (2012). Working memory and individual differences in the encoding of vertical, horizontal and diagonal symmetry. *Acta Psychologica*, 141(1), 122–132. doi:10.1016/j.actpsy.2012.06.007
- Rossi-Arnaud, C., Spataro, P., & Longobardi, E. (2012). Effects of pointing on the recall of simultaneous and sequential visuospatial arrays: A role for retrieval strategies? *Psychological Research*, 76(6), 699–712. doi:10.1007/s00426-011-0394-8
- Saito, S., Logie, R. H., Morita, A., & Law, A. (2008). Visual and phonological similarity effects in verbal immediate serial recall: A test with kanji materials. *Journal of Memory and Language*, 59(1), 1–17. doi:10.1016/j.jml.2008.01.004
- Schumann-Hengsteler, R., Strobl, M., & Zoelch, C. (2004). Temporal memory for locations: On the coding of spatiotemporal information in children and adults. In Gary L. Allen (Ed.), *Human memory: Remembering where* (125-142). Mahwah, NJ, US: Lawrence Erlbaum Associates.
- Schunn, C. D., & Reder, L. M. (1998). Strategy adaptivity and individual differences. In D. L. Medin & D. L. Medin (Eds.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 38, pp. 115–154). San Diego, CA: Academic Press.
- Schunn, C. D., & Reder, L. M. (2001). Another source of individual differences: Strategy adaptivity to changing rates of success. *Journal of Experimental Psychology: General*, 130, 59–76. <http://dx.doi.org/10.1037/0096-3445.130.1.59>
- 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. doi:10.1037/0096-3445.125.1.4
- Siegler, R. S. (1987). The perils of averaging data over strategies: An example from children's addition. *Journal of Experimental Psychology: General*, 116(3), 250–264. doi:10.1037/0096-3445.116.3.250
- Silvis, J. D., & Shapiro, K. L. (2014). Spatiotemporal configuration of memory arrays as a component of VWM representations. *Visual Cognition*, 22(7), 948–962. doi:10.1080/13506285.2014.937789
- Simmering, V. R., & Perone, S. (2013). Working memory capacity as a dynamic process. *Frontiers in Psychology*, 3. doi:10.3389/fpsyg.2012.00567
- Smith, G. G., Ritzhaupt, A. D., & Tjoe, E. (2010). Strategies in visuospatial working memory for learning virtual shapes. *Applied Cognitive Psychology*, 24(8), 1095–1114. doi:10.1002/acp.1620
- Souza, A. S., & Skóra, Z. (2017). The interplay of language and visual perception in working memory. *Cognition*, 166, 277–297. doi:10.1016/j.cognition.2017.05.038
- Spataro, P., Marques, V. R. S., Longobardi, E., & Rossi-Arnaud, C. (2015). Does pointing facilitate the recall of serial positions in visuospatial working memory? *Cognitive Processing*, 16(Suppl 1), 377–381. doi:10.1007/s10339-015-0681-1

- Starc, M., Anticevic, A., & Repovs, G. (2017). Fine-grained versus categorical: Pupil size differentiates between strategies for spatial working memory performance. *Psychophysiology*, 54(5), 724–735. doi:10.1111/psyp.12828
- Strasser, I., Koller, I., Strauß, S., Csisinko, M., Kaufmann, H., & Glück, J. (2010). Use of strategy in a 3-dimensional spatial ability test. *Journal of Individual Differences*, 31(2), 74–77. doi:10.1027/1614-0001/a000013
- Sullivan, E. V., Mathalon, D. H., Ha, C. N., Zipursky, R. B., & Pfefferbaum, A. (1992). The contribution of constructional accuracy and organizational strategy to nonverbal recall in schizophrenia and chronic alcoholism. *Biological Psychiatry*, 32(4), 312–333. doi:10.1016/0006-3223(92)90036-Y
- Sun, H., Zimmer, H. D., & Fu, X. (2011). The influence of expertise and of physical complexity on visual short-term memory consolidation. *The Quarterly Journal of Experimental Psychology*, 64(4), 707–729. doi:10.1080/17470218.2010.511238
- Thalmann, M., Souza, A. S., & Oberauer, K. (2019). How does chunking help working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 45(1), 37–55. doi:10.1037/xlm0000578
- Treisman, A., & Zhang, W. (2006). Location and binding in visual working memory. *Memory & Cognition*, 34(8), 1704–1719. doi:10.3758/BF03195932
- Tremblay, S., Saint-Aubin, J., & Jalbert, A. (2006). Rehearsal in serial memory for visual-spatial information: Evidence from eye movements. *Psychonomic Bulletin & Review*, 13(3), 452–457. doi:10.3758/BF03193869
- Turley-Ames, K. J., & Whitfield, M. M. (2003). Strategy training and working memory task performance. *Journal of Memory and Language*, 49(4), 446–468. doi:10.1016/S0749-596X(03)00095-0
- Tversky, B. (2005). Visuospatial Reasoning. In K. J. Holyoak & R. G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (p. 209–240). Cambridge, UK: Cambridge University Press.
- Udale, R., Farrell, S., & Kent, C. (2018). No evidence of binding items to spatial configuration representations in visual working memory. *Memory & Cognition*, 46(6), 955–968. doi:10.3758/s13421-018-0814-8
- Uttal, D. H., & Chiong, C. (2004). Seeing space in more than one way: Children's use of higher order patterns in spatial memory and cognition. In Gary L. Allen (Ed.), *Human memory: Remembering where* (125–142). Mahwah, NJ, US: Lawrence Erlbaum Associates.
- Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M., & von der Heydt, R. (2012). A century of Gestalt psychology in visual perception: I Perceptual grouping and figure–ground organization. *Psychological Bulletin*, 138(6), 1172–1217. doi:10.1037/a0029333

- Woodman, G. F., Vecera, S. P., & Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomic Bulletin & Review*, 10(1), 80–87. doi:10.3758/BF03196470
- Woodman, G. F., Vogel, E. K., & Luck, S. J. (2012). Flexibility in visual working memory: Accurate change detection in the face of irrelevant variations in position. *Visual Cognition*, 20(1), 1–28. doi:10.1080/13506285.2011.630694
- Xu, Y. (2006). Understanding the object benefit in visual short-term memory: The roles of feature proximity and connectedness. *Perception & Psychophysics*, 68(5), 815–828. doi:10.3758/BF03193704
- Xu, Y., & Chun, M. M. (2007). Visual grouping in human parietal cortex. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, 104(47), 18766–18771. doi:10.1073/pnas.0705618104
- Zimmermann, K., & Eschen, A. (2017). Brain regions involved in subprocesses of small-space episodic object-location memory: A systematic review of lesion and functional neuroimaging studies. *Memory*, 25(4), 487–519. doi:10.1080/09658211.2016.1188965
- Zoelch, C., & Schumann-Hengsteler, R. (2006). Aspects of complexity in visual–spatial working memory: indication for the application of strategies? *Cognitive Processing*, 7(suppl. 1), 165–165. doi:10.1007/s10339-006-0125-z