

A Core Knowledge Architecture of Visual Working Memory

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Visual working memory (VWM) is widely thought to contain specialized buffers for retaining spatial and object information: a ‘spatial-object architecture.’ However, studies of adults, infants, and nonhuman animals show that visual cognition builds on core knowledge systems that retain more specialized representations: (1) spatiotemporal representations for object tracking, (2) object identity representations for object recognition, and (3) view-dependent snapshots for place recognition. In principle, these core knowledge systems may retain information separately from one another. Consistent with this hypothesis, this study provides evidence that these three types of information are subject to independent working memory storage limits. These results, combined with those from previous studies, indicate that VWM contains three specialized buffers for retaining spatiotemporal information, object identity information, and snapshot information. Thus, VWM buffers parallel core knowledge systems. This ‘core knowledge architecture’ links the study of visual working memory to the study of the biological foundations of visual cognition.

Keywords: visual working memory, visual short-term memory, core knowledge, cognitive development, animal cognition

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How do people retain visual information about the environment? For decades, many researchers have argued that visual cognition depends on a visual working memory (VWM) mechanism with two primary components: one for retaining spatial (‘where’) information and one for retaining object (‘what’) information. Suggestive evidence for this ‘spatial-object architecture’ comes from studies of human adults, who recruit different cognitive processes, supported by distinct neural substrates, during working memory tasks for locations versus objects. More recently, however, studies of adults, infants, and nonhuman animals have shown that visual cognition builds on innate,¹ evolutionarily ancient systems that retain more specialized representations: *spatiotemporal* representations for object tracking, *object property/kind* representations for object recognition, and *view-dependent snapshot* representations for place recognition. In principle, each of these core knowledge systems may use a separate buffer to retain information: a ‘core knowledge architecture’ of VWM. Here I review research on the core knowledge systems that support visual cognition from infancy to adulthood. Then I review studies investigating the architecture of VWM. These studies provide suggestive evidence for a core knowledge architecture of VWM because observers retained information about spatiotemporally defined

movements, object properties/kinds, and view-dependent snapshots in separate, specialized VWM buffers. Finally, I present the results of eight experiments that test, and confirm, a number of additional predictions of this core knowledge architecture. I conclude that VWM is best understood as a collection of components that parallel the core knowledge systems that structure visual experience from infancy to adulthood.

Core Knowledge Systems in Adults, Infants, and Nonhuman Animals

The term ‘core knowledge’ comes from a rich research tradition that seeks to characterize the psychological and neural mechanisms that provide the foundations for cognition (Carey, 2009; Hauser & Spelke, 2004; Spelke, 2000). Core knowledge systems emerge early in human development and thus are common to infants, children, and adults. Core knowledge systems are also evolutionarily ancient and thus are shared with many nonhuman species. More specifically, a core knowledge system is typically characterized by four properties (see Hauser & Spelke, 2004). First, it is domain-specific: each system functions to represent a particular kind of entity (e.g., individual objects, object kinds, and places in the environment). Second, a core knowledge system is task-specific: each system uses its representations to address specific questions about the world (e.g., “where is it?” [object tracking], “what is this?” [object recognition], and “where am I?” [place recognition]). Third, a core knowledge system is encapsulated:

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¹ By *innate* I simply mean *not learned*. Learning mechanisms necessarily require unlearned abilities for detecting and analyzing inputs and for drawing inferences, and so claims of learning inevitably presuppose a set of innate capacities (see Spelke & Newport, 1998).

each system uses only a subset of the information delivered by the animal's input systems and sends information only to a subset of the animal's output systems. Fourth, a core knowledge system is relatively automatic and impervious to explicitly held beliefs.

I focus on three core knowledge systems that underlie visual-cognitive abilities in diverse animals: (1) an object tracking system that maintains spatiotemporal information, (2) an object recognition system that maintains identity information, and (3) a place recognition system that maintains view-dependent snapshots of previously occupied places.

Spatiotemporal Representations for Object Tracking

Converging evidence from studies of adults, infants, and non-human animals show that individuals use spatiotemporal representations to individuate and track objects (reviewed by Flombaum, Scholl, & Santos, 2008). These representations include information about where and when objects were encountered. For instance, when observers see an object pass behind a screen and then an object emerge from the opposite side of the screen, they perceive a single persisting object (Burke, 1952; Michotte et al., 1964). However, if the spatiotemporal properties of the movements are not quite right for amodal integration (e.g., if the disoccluding object emerges at the wrong time or place), observers see two distinct objects—one that disappears behind the screen and another that later emerges. Importantly, this process is blind to the surface properties of the objects. For instance, two objects with different color or shape properties are perceived as the same object when they move along the same spatiotemporal path. This visual phenomenon is known as the 'tunnel effect' (Burke, 1952; Michotte et al., 1964/1991).

Converging evidence that separate systems are used to track objects and identify objects comes from studies of apparent motion and multiple object tracking. In apparent motion, we perceive a continuous motion trajectory when an object appears in one location, disappears, and then an object appears in another nearby location (Anstis, 1980; Wertheimer, 1912). As in the tunnel effect, apparent motion depends primarily on spatiotemporal factors (Dawson, 1991; Kolers, 1972): we perceive apparent motion even when the two discrete objects look different from one another (provided that the objects appear close enough in time and space), and we fail to perceive apparent motion when the objects are not sufficiently close in time and space (even when the objects have identical surface properties). In multiple object tracking, observers are shown a display with many individual objects and are asked to keep track of a subset of those objects as they move independently from one another (Pylyshyn, 2001; Pylyshyn & Storm, 1998). Object tracking depends primarily on the spatiotemporal properties of the objects; for example, tracking is not disrupted when the objects change color, size, shape, or kind during their motion. Furthermore, if a tracked object disappears, observers can report the object's last seen location and direction of motion, but fail to report the object's last seen color or shape (Scholl, Pylyshyn, & Franconeri, 1999). When tracking objects, observers can therefore retain and update information about the location and direction of motion of the objects *without* retaining and updating information about the colors and shapes of the objects.

Studies from developmental psychology show that spatiotemporal representations guide object individuation and tracking early

in life (reviewed by Spelke, 1990). For example, Kellman and Spelke (1983) presented infants with a partly occluded object on a series of habituation trials. A screen covered the middle of the object, with part of the object visible above the screen and part of the object visible below the screen. After the habituation trials, the screen was removed and infants were shown two different test displays: (1) a complete, connected object, and (2) a fragmented object that consisted of the surfaces of the object that had been visible in the habituation trials. Infants perceived a complete, connected object from the habituation displays when the two parts of the object moved together behind the screen. In contrast, non-movement properties such as color, shape, and texture did not affect infants' object perception (Kellman & Spelke, 1983; Termine, Hyrnick, Kestenbaum, Gleitman, & Spelke, 1987). Thus, young infants analyze the movements of surfaces to segment the visual scene into objects. Two related findings reinforce the importance of movement information in object individuation. First, newborn infants use movement information to individuate objects (Valenza, Leo, Gava, & Simion, 2006). Second, congenitally blind adults who recover vision after treatment use movement information to segment the visual scene into objects (Ostrovsky et al., 2009). For these patients, prominent featural cues (e.g., good continuation, junction structure) were largely ineffective for object parsing, whereas movement cues strongly facilitated object individuation. Thus, spatiotemporal information plays a fundamental role in organizing visual experience during both infancy and adulthood.

Other studies show that young infants retain spatiotemporal information, including the number of movements performed by an object (Sharon & Wynn, 1998; Wood & Spelke, 2005; Wynn, 1996). Further, like adults, infants analyze possible paths connecting the appearances of objects at different points in time, inferring from spatiotemporal discontinuities in motion the number of numerically distinct objects in the scene (e.g., Aguiar & Baillargeon, 1999; Spelke, Kestenbaum, Simons, & Wein, 1995; Wynn, 1992).

Comparative studies provide evidence that this object tracking system is shared with a wide range of animals, including primates and birds. For instance, like human adults, rhesus monkeys perceive the tunnel effect illusion (Flombaum et al., 2004). When rhesus monkeys observe a lemon roll behind a screen and then a kiwi emerge at the time that the lemon should have, monkeys search as if there is just one object, despite seeing two different kinds of objects. In addition, rhesus monkeys can track up to 3–4 objects at once (Barner, Wood, Hauser, & Carey, 2008; Hauser, Carey, & Hauser, 2000), a limit that matches the number of objects that human infants and adults can track at once (Feigenson, Carey, & Hauser, 2002; Scholl, 2001). In precocial animals, such as the domestic chick, spatiotemporal information can be seen guiding object tracking in the first days of life. Like human infants, young chicks perceive the complete shapes of partly occluded objects based on an analysis of spatiotemporal relationships revealed over object motion (O'Reilly & Johnson, 1994; Regolin & Vallortigara, 1995). Furthermore, when 2-day-old chicks imprint to an object they will track that object as it moves around the environment. For instance, if their imprinted object moves out of view behind a screen, the chicks will search for the object behind the screen (Regolin et al., 1995; Rugani et al., 2009). This behavior appears even when the chick has never before witnessed an object being hidden by another object.

In summary, studies of adults, infants, and nonhuman animals provide evidence for a core object tracking system that analyzes and retains spatiotemporal information.

Property/Kind Representations for Object Recognition

Although spatiotemporal representations support our ability to track objects as they move, they are not sufficient for identifying different kinds of objects. For example, if we see an object in the sky, spatiotemporal representations would support our ability to track that object as it moves, but would not support our ability to identify that object as a bird or a plane. Identifying objects as particular *kinds* requires a separate object recognition system that analyzes shape and color information.²

The capacity to reason about objects as different *kinds* of things, like “chairs” and “apples,” allows us to develop expectations about both the observable properties of these kinds and their unobservable properties, which we can infer in the absence of direct perceptual experiences. This ability to retain object kind information supports ‘psychological essentialism,’ the belief that certain categories possess an intrinsic and unchanging nature that plays a causal role in category membership. Based on evidence that young children use category membership to infer an object’s unseen properties (reviewed by Gelman, 2003, 2004), many developmental psychologists argue that psychological essentialism reflects an innate core architecture that helps us to reason about the category structure of the world (e.g., Keil, 1989).

This proposal is supported by decades of experimentation on form perception and object recognition in adults, infants, and nonhuman animals, which provide evidence for a core knowledge system for recognizing movable, manipulable objects (Gibson, 1969; Izard & Spelke, 2009; Spelke, Lee, & Izard, 2010). Research on object recognition shows that objects are best recognized by their shape, beginning early in development (Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002) and continuing through adulthood (Biederman, 1987). Studies of young infants, some tested only a few hours after birth, provide evidence for an early emerging object recognition system that is sensitive to angle and length information (Newcombe, Huttenlocher, & Learmonth, 1999; Schwartz & Day, 1979; Slater, Mattock, Brown, & Bremner, 1991). Other studies show that young infants use property information as the basis for individuating visual objects from one another. By 4.5 months infants can use shape and size information as the basis for individuation, by 7.5 months infants can also use pattern information, and by 11.5 months infants can also use color and luminance information (Wilcox, 1999; Woods & Wilcox, 2006). Between 10 and 12 months of age, infants also begin to use property differences that distinguish basic-level categories to individuate objects in a scene: 10-month-old infants who observe two different objects, such as a duck and a ball, emerge and return one at a time from behind a screen infer the existence of just one object behind the screen, whereas 12-month-old infants correctly infer the existence of two objects (Xu & Carey, 1996).

Object recognition also appears to be universal across cultures. For example, when recognizing objects Western observers are more sensitive to *nonaccidental properties*, such as whether a given contour is straight or curved or whether the type of vertex formed by the co-termination of contours is a Y, L, or an arrow, than to *metric properties*, such as length or aspect ratio, angles of inter-

sections, and degrees of curvature (Biederman, 1987). Similarly, the Himba, a seminomadic people living in a remote region of Namibia where there is little exposure to regular, simple artifacts, show the same greater sensitivity to nonaccidental properties than to metric properties when recognizing objects (Biederman, Yue, & Davidoff, 2009).

Two other sets of findings provide evidence for a core object recognition system. First, object shape is processed by dedicated regions in the lateral occipital and temporal cortex, both in humans (Grill-Spector, Golarai, & Gabrieli, 2008; Kourtzi & Kanwisher, 2001; Reddy & Kanwisher, 2006) and in nonhuman primates (Kriegeskorte et al., 2008; Tanaka, 1996; Yamane, Carlson, Bowman, Wang, & Conner, 2008). Second, many nonhuman animals recognize objects in the same way as humans. Like human infants, both mammals and birds identify and individuate objects on the basis of property/kind information (Clayton & Dickinson, 1999; Munakata, Santos, Spelke, Hauser, & O’Reilly, 2001; Phillips & Santos, 2007; Phillips, Shankar, & Santos, 2010; Santos, Sulkowski, Spaepen, & Hauser, 2002; Uller, Xu, Carey, & Hauser, 1997). Also like humans, many animals—including monkeys and pigeons—show greater sensitivity to nonaccidental properties than to metric properties when recognizing objects (Gibson, Lazareva, Gosselin, Schyns, & Wasserman, 2007; Vogels, Biederman, Bar, & Lorincz, 2001). Thus, the early developing object recognition system used by humans is also used by a wide range of animals to recognize and individuate objects.

In summary, studies of adults, infants, and nonhuman animals provide evidence for a core object representation system that analyzes and maintains property/kind information such as color, shape, and category membership.

View-Dependent Snapshot Representations for Place Recognition

The core knowledge systems for object tracking and object recognition process information about individual objects. In addition to these object representation systems, adults, infants, and nonhuman animals also use a view-based visual homing system to navigate the environment (Cartwright & Collett, 1983; Collett & Collett, 2000). Specifically, animals take a snapshot of the scene surrounding a target goal (e.g., a nest) and store this view in memory. During navigation, the animal moves to recover this target view so as to reduce the difference between the current view and the target view.

Evidence for snapshot representations comes from studies of navigating insects and mammals. Bees, for example, were trained

² The distinction between object tracking and object recognition can be illustrated by the following example (Leslie, Xu, Tremoulet, & Scholl, 1998). Consider watching someone remove objects from a bag then place those objects in a box, one at a time. If asked, ‘How many objects are in the box?’, one could answer this question by tracking the number of objects that moved from the bag to the box. One would not need to remember the kinds of the objects placed in the box. Spatiotemporal representations would suffice to individuate the objects in this task. However, if asked, ‘What objects are in the box?’, spatiotemporal representations would not be sufficient to answer this question. Rather, one would need to analyze property information to identify each object and remember what each object was.

to forage in an environment filled with landmarks and then the food source and the landmarks were moved to different locations. Bees approached the food source from a constant direction, so that the visual image of the scene was roughly the same each time they approached the food (Collett & Lehrer, 1993; Collett & Rees, 1997). Some insects such as wood ants store multiple snapshots of a familiar landmark from different vantage points so that they may approach a familiar landmark from multiple angles (Judd & Collett, 1998). Snapshot representations also guide visual navigation in rodents and humans. For instance, rodents in a water maze tend to approach a hidden support from a particular direction (Sutherland et al., 1987). Similarly, human adults readily learn locations in virtual reality environments defined entirely by a continuous color gradient without individual objects that may be used as landmarks, in qualitative agreement with a view-dependent snapshot system but not with other models of place recognition (Gillner, Weib, & Mallot, 2008).

Importantly, a snapshot representation contains the set of sensory readings obtained at a particular location (Trullier, Wiener, Berthoz, & Meyer, 1997). Snapshot representations can therefore be thought of as “memories of perceptions” rather than as “memories of actual real world objects” (Siegel & White, 1975).

Summary

Although the human cognitive system is more complex than that of any other animal, studies of adults, infants, and nonhuman animals provide evidence that humans inherited much of the same machinery that is found throughout the animal kingdom. Further, much of this machinery remains present and functional from infancy to adulthood (Carey, 2009; Spelke & Kinzler, 2007).

Specifically, visual cognition builds on at least three evolutionarily ancient systems: (1) an object tracking system that analyzes and maintains spatiotemporal information; (2) an object recognition system that identifies objects on the basis of property information; and (3) a place recognition system that uses view-dependent snapshot representations to determine the organism’s location in the environment. These systems guide behavior in closely and distantly related animals, including, for the case of view-dependent place recognition, animals with cognitive systems as simple as ants.

Critically, how do these core knowledge systems retain visual information? Each of these systems requires a temporary buffer, known as VWM (also known as visual short-term memory), to retain information over time: (1) The object tracking system requires a ‘spatiotemporal-based’ memory mechanism that retains information about the locations of objects at different points in time; (2) The object recognition system requires an ‘object-based’ memory mechanism that retains information about the identities and properties of objects across visual interruptions; and (3) The place recognition system requires a ‘snapshot-based’ memory mechanism that retains visible features across eye movements and over time.

Do these core knowledge systems depend on the same VWM system to retain information? In principle, they might. Alternatively, these core knowledge systems might depend on separate, specialized mechanisms for retaining spatiotemporal information, object property/kind information, and view-dependent snapshot information: a core knowledge architecture of VWM.

This core knowledge architecture can explain a number of puzzling findings in the literature. First, this architecture provides a straightforward account for how observers can update information about an object’s movement without updating information about the object’s color and shape, because observers retain spatiotemporal information in one VWM system and object property/kind information in a separate VWM system. Second, this architecture provides an account of how VWM retains both 3D object information and view-dependent snapshot information. These are incompatible types of information (i.e., view-dependent snapshots contain relatively unprocessed sensory information, whereas 3D object representations contain identity information which is independent of the particular sensory information used to recognize the object), and so VWM must have specialized components to retain these different types of information. According to the core knowledge architecture, 3D object information and view-dependent snapshot information are retained in separate ‘object-based’ and ‘snapshot-based’ mechanisms, respectively. Third, the core knowledge architecture provides a straightforward account for the considerable variation in VWM storage capacity obtained across studies. Specifically, studies examining VWM for the properties of moving objects or the identities of 3D objects typically report storage capacity estimates of about two objects (e.g., Rasmussen & Hollingworth, 2008; Saiki, 2003; Wood, 2009), whereas studies examining VWM for features in a scene often report storage capacity estimates of up to 3-4 objects (e.g., Luck & Vogel, 1997; Wood, 2009). According to the core knowledge architecture, these different storage limits reflect different memory mechanisms, one for object-based information and one for snapshot-based information.

In what follows, I review studies that provide more direct evidence for the core knowledge architecture of VWM.

The Architecture of VWM

Studies of infants and animals show that visual cognition builds on at least three separate, specialized systems of visual representation. Each of these systems may require its own buffer to retain information over time. These results conflict with traditional models of the architecture of VWM, which is widely thought to contain just two components: one for retaining spatial information and one for retaining object information. How may these different views be reconciled with one another?

The spatial-object architecture is supported by three main findings: (1) there is less interference between an object memory task and a spatial memory task than between two object memory tasks or between two spatial memory tasks (e.g., Klauer & Zhao, 2004; Logie, 1986; Logie & Marchetti, 1991; Logie & Pearson, 1997; Smyth & Scholey, 1994); (2) brain damage can impair object memory or spatial memory without impairing the other type of memory (e.g., Carlesimo, Perri, Turriziani, Tomaiuolo, & Caltagirone, 2001; Farah, Hammond, Levine, & Calvanio, 1988; Hanley, Young, & Pearson, 1991; Owen, Iddon, Hodges, Summers, & Robbins, 1997; Postle, Jonides, Smith, Corkin, & Growdon, 1997); and (3) object memory tasks activate different neural substrates than spatial memory tasks (e.g., Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; McCarthy, Puce, Constable, Krystal, Gore, & Goldman-Rakic, 1996; Smith, Jonides, Koeppel, Awh, Schumacher, & Minoshima, 1995). Critically, this evidence is also con-

sistent with the core knowledge architecture of VWM because the core knowledge systems reviewed above selectively retain spatial information and object information. Spatiotemporal representations and view-dependent snapshot representations both contain spatial information, and object property/kind representations and view-dependent snapshot representations both contain object feature information. Thus, the working memory dissociations observed in previous studies could have resulted from either object and spatial memory systems or from more specialized memory systems that retain spatiotemporal information, object property/kind information, and view-dependent snapshot information.

The core knowledge architecture can be distinguished from the spatial-object architecture by investigating VWM for spatiotemporal information, object property/kind information, and view-dependent snapshot information. The core knowledge architecture predicts that these three types of information are stored in separate, specialized memory systems. Thus, all three types of information should be subject to independent working memory storage limits. This generates three more specific empirical predictions: (1) memory for spatiotemporally defined movements will not compete with memory for object properties/kinds for the limited storage resources of a single VWM system; (2) memory for object properties/kinds will not compete with memory for view-dependent snapshots for the limited storage resources of a single VWM system; and (3) memory for view-dependent snapshots will not compete with memory for spatiotemporally defined movements for the limited storage resources of a single VWM system.

In contrast, according to the spatial-object architecture, separate working memory systems retain spatial and object information. This predicts that any two memory tasks that require retaining spatial information or require retaining object information will compete with one another for the limited storage resources of the spatial memory system or the object memory system, respectively. Unlike the core knowledge architecture, the spatial-object architecture must predict that object property/kind information and view-dependent snapshot information will be retained in the same object working memory system because both require memory for nonspatial featural information, such as color and shape.³ In addition, unlike the core knowledge architecture, the spatial-object architecture must predict that spatiotemporal information and view-dependent snapshot information will be retained in the same spatial working memory system because both require memory for spatial information.

Recent studies confirm all three of these specific empirical predictions of the core knowledge architecture. In contrast, they do not support these specific predictions of the spatial-object architecture. I describe these studies in more detail below.

Dissociating Object-Based and Snapshot-Based VWM

Wood (2009) provided evidence that object property/kind information and view-dependent snapshot information are stored in separate VWM systems. Specifically, when participants were asked to remember 3D objects over a one or few second delay interval, they could retain information about the identities of only 1-2 objects; in addition, however, they could also retain information about other objects in the scene using view-dependent representations. Thus, observers retained two types of visual informa-

tion: information about individual objects and information about view-dependent features.

In addition, Wood (2009) showed that VWM is subject to independent storage limits for retaining information about individual objects and for retaining information about features in a scene. In a dual-task experiment, participants attempted to remember the identities of as many 3D objects as possible in the first memory task and as many colored squares in a scene⁴ as possible in the second memory task. Participants could remember the identities of 1-2 3D objects independent of whether they performed the first memory task alone or concurrently with the second memory task, and 3-4 color features in a scene independent of whether they performed the second memory task alone or concurrently with the first memory task. This kind of independence between concurrently performed working memory tasks indicates that separate buffers are used to perform the tasks. Thus, VWM contains separate, specialized components for retaining object identity information and information about features in the scene. The spatial-object architecture cannot account for this finding because both memory tasks required memory for nonspatial feature information. Thus, the object representations from the two memory tasks should have competed with one another for the limited storage resources of a single VWM system, thereby making it significantly more difficult to perform the tasks concurrently compared to separately.

Hollingworth & Rasmussen (2010) provide convergent evidence that separate VWM components retain information about individual objects and information about features in a scene. Participants were asked to remember the colors of objects that appeared briefly in a set of boxes. Then, the empty boxes moved so as to trade locations, and test colors appeared. The results provided evidence for two types of representation. First, VWM bound color information to the moving objects. Second, VWM bound color

³ Many studies have examined how object information is retained in VWM and the results from these studies have traditionally been interpreted as reflecting properties of a single system (e.g., Luck & Vogel, 1997). However, most studies have investigated memory for 2D stimuli, such as colored squares and oriented lines in a scene. This makes it difficult to determine whether subjects remembered the items using object property/kind representations or view-dependent snapshot representations because most 2D stimuli can be successfully remembered using both types of representation (i.e., the items in the study and test displays could have been compared on the basis of either the properties/identities of individually represented objects or on the basis of sensory information stored in a view-dependent snapshot). Thus, many previous studies may have inadvertently elicited representations from two different VWM systems, one that retains object-based information and one that retains snapshot-based information (see Wood, 2009, for evidence supporting this possibility).

⁴ Color values were used for three reasons. First, they are arguably the most simple, suprathreshold feature that can be retained in VWM (Luck & Vogel, 1997). Second, color values have been used extensively to study properties of VWM, which creates a link between these findings and previous studies. Third, studies show that color information can guide human navigation via view-dependent snapshot representations. For example, Gillner and colleagues (2008) showed that place recognition during navigation can be based solely on smooth variations of color in the visual snapshot, in qualitative agreement with a view-matching snapshot system. Other experiments in Wood (2009) specifically examined the view-dependence of VWM representations.

information to their original locations. Thus, participants retained both properties of individual objects and features of the scene.

Dissociating Spatiotemporal-Based and Snapshot-Based VWM

Wood (2007) provided evidence that spatiotemporal information and view-dependent snapshot information are stored in separate VWM systems. In a dual-task paradigm, participants attempted to remember as many spatiotemporally defined movements as possible in the first memory task and as many colored squares in a scene as possible in the second memory task. Participants could remember about two movements independent of whether they performed the first memory task alone or concurrently with the second memory task, and 3-4 colored squares in a scene independent of whether they performed the second memory task alone or concurrently with the first memory task. Thus, the two working memory tasks did not compete with one another for the limited storage resources of a single VWM system, which indicates that VWM contains separate mechanisms for retaining spatiotemporal information and information about features in the scene.

Furthermore, Wood (2007) used this dual-task paradigm to show that information about spatiotemporally defined movements is stored in a separate VWM system from information about the locations of dots in a scene (see also Zimmer, Speiser, & Seidler, 2003). The spatial-object architecture cannot account for this finding because both the movement memory task and the location memory task required retaining spatial information. Thus, the spatial information retained for the two memory tasks should have competed for the limited storage resources of a single VWM system, thereby making it significantly more difficult to perform the tasks concurrently compared to separately.

Wood (2007) also showed that the movement representations retained in VWM do, in fact, contain both spatial and temporal information. Specifically, observers retain information about both the spatial characteristics of movements and the durations of those movements, and these two types of information are bound together as integrated spatiotemporal representations in VWM.

Dissociating Spatiotemporal-Based and Object-Based VWM

Wood (2008) provided evidence that spatiotemporally defined movement information and object property/kind information are stored in separate VWM systems. On each trial, participants viewed a study sequence consisting of three different objects (3D human figures that were uniquely defined by color), each of whom performed a single movement. Then, a test figure appeared and performed a movement, and participants indicated whether that event matched an event from the study sequence. Results showed that participants could retain information about both 2-3 figures and 2-3 movements concurrently. However, they were highly impaired for remembering *which* figure performed *which* movement. For example, after observing a man wearing green raise his arm, participants might remember having seen both a man wearing green and an arm raise movement, but fail to remember that it was the man wearing green who had raised his arm. Thus, the color information that defined the figures and the movements performed

by the figures were retained in memory, but not as integrated representations. This suggests that representations of color properties and spatiotemporal representations of movements are retained separately in VWM.

Outline of the Current Experiments

The studies reviewed above suggest that VWM can be divided into separate systems for retaining spatiotemporal information, object property/kind information, and view-dependent snapshot information. In what follows, I present the results of eight new experiments that test additional predictions of the core knowledge architecture. Experiments 1-5 provide further evidence that VWM can be divided into separate systems for retaining spatiotemporal information and object property information. Experiment 6 provides further evidence that VWM can be divided into separate systems for retaining spatiotemporal information and snapshot information. Finally, Experiments 7-8 show that VWM can be divided into separate systems for retaining object property information and snapshot information, even when the two types of information are defined by features from the same feature dimension of color. These results converge in all respects with predictions of the core knowledge architecture.

Experiment 1

To test how VWM retains spatiotemporal information and object property information, I first measured the storage capacity of VWM for simple, suprathreshold items. On each trial, participants viewed a study sequence containing 1-5 spatiotemporally defined movements or 1-5 object color properties, followed by a test movement or color, and then indicated whether that test item had been present in the study sequence. In the movement memory task, participants attempted to remember simple movements performed by a computer-generated human figure (see Figure 1A). In the object property memory task, a 3D sphere changed to different colors and participants attempted to remember those colors. Color changes were used to study object property representation for two reasons. First, color values are arguably the most simple property that can be retained as part of an object. Second, by using color changes rather than colored objects, it was possible to present multiple color values on a single enduring 3D object, thereby placing only minimal demands on extrinsic processes such as object-based attention.

Method

Participants. Ten participants (male: 7, female: 3; mean age = 21.1 years, $SD = 2.85$) with normal or corrected-to-normal vision took part to receive credit toward a course requirement or for monetary payment. Informed consent was obtained.

Procedure. The experiment was conducted on a 17" monitor. Each trial began with a 1,000-ms presentation of two randomly selected letters and participants were required to repeat those letters continuously and out loud until the end of the trial. This articulatory suppression task inhibits the use of verbal coding in memory tasks (Besner, Davies, & Daniels, 1981; Wood, 2009). The offset of these letters was followed by a 500-ms presentation of a screen displaying the word "ready," followed by the presen-

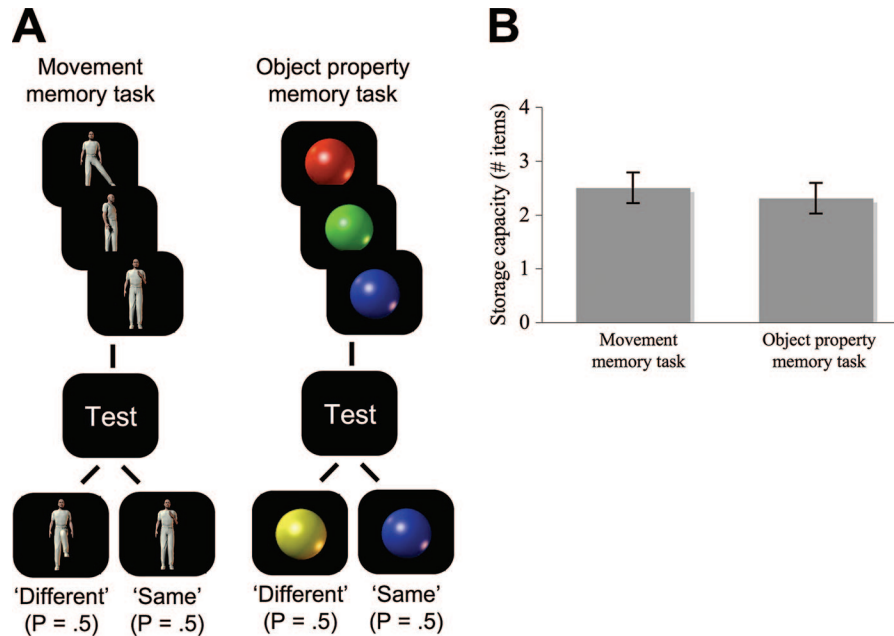


Figure 1. (A) Flow chart of events for Experiment 1. In the movement memory task condition, participants attempted to remember 1–5 movements. In the object property memory task condition, participants attempted to remember 1–5 color changes. (B) Average number of items that could be retained at once for the movement memory task and the object property memory task. Error bars represent *SE*.

tation of the study sequence. In the movement memory task, the study sequence consisted of 1–5 movements performed by a computer-generated figure subtending 10.5° (height) \times 4° (width) at the center of a video monitor with a black background. The animations were created using Poser 6 software from SmithMicro. All movements were dynamic (i.e., they involved fluid, continuous movement, rather than being presented as static pictures). Each movement lasted 500 ms and was preceded by 500 ms of stasis. During the 500-ms period of stasis between movements the figure was in a neutral position. The movements were selected at random from a set of seven highly discriminable movements (see Appendix 1A in the online supplementary materials). Each movement could occur only once in the sequence. The figure performed each movement on the left side of his body.

The object property memory task was identical to the movement memory task except the study sequence consisted of 1–5 color changes in which a white 3D sphere ($2 \times 2^\circ$) changed gradually to one of seven highly discriminable colors (blue, green, dark brown, orange, purple, red, yellow; see Appendix 1A in the online supplementary materials) and then changed back to white. A 500-ms interval of stasis divided each color change. To be clear, participants did not need to remember the neutral white colors. Rather, they were instructed to remember the nonwhite colors that the object changed to during the events.

After a 500-ms delay, there was a 1,000-ms presentation of the word “test,” followed by the presentation of the test movement or color. Participants indicated whether that test item had been present in the study sequence, which was the case on 50% of the trials.

The movement and object property memory tasks were conducted in separate blocks, counterbalanced across participants. Participants received 30 trials per set size (1–5) in each memory task.

Results and Discussion

To provide a quantitative analysis of storage capacity, the data were converted into storage capacity estimates by using the formula developed by Cowan (2001). The logic of this approach is that if an observer can retain K items in memory from a set of S items, then the item that changed should be one of the items being held in memory on K/S trials, leading to correct performance on K/S of the trials on which an item changed. This measure takes into consideration the effects of guessing, by factoring in the false alarm rate [F = false alarms/(false alarms + correct rejections)] and the observed hit rate [H = hits/(hits + misses)]. The formula is defined as $K = S(H - F)$.⁵

Figure 1B illustrates the results. The capacity estimates were averaged for set sizes 3–5 from each memory task (see Appendix 1B in the online supplementary materials for the hits and false alarms for all set sizes across tasks). In the movement memory task, participants could remember up to 2.50 movements. In the object property memory task, participants could remember up to 2.31 colors. These storage capacity estimates did not differ significantly from one another, $F(1, 9) = 0.67$, $p = .44$, $h_p^2 = .07$. Thus, the storage capacity of VWM for both movements and object colors is 2–3 items. These storage capacities converge with those

⁵ Cowan’s (2001) formula is the most widely accepted method for quantifying storage capacity. It is worth noting, however, that a recent study provides a promising new way to measure memory capacity by adding a third response option (Kyllingsbæk & Bundesen, 2009). In addition to “change” or “no change,” the participant can also indicate that the probed item was not encoded by responding “I don’t know.” This added response option reduces the variance of the capacity estimate substantially.

reported in previous studies that used a similar methodology (Wood, 2007, 2008).

What is the architecture of the VWM system that retains movement information and object property information? One possibility is that VWM retains movement and object property information in the same memory system. This predicts that VWM capacity will depend on the total number of items retained in memory, irrespective of whether the items are movements or object properties. Alternatively, VWM might retain movement and object property information in separate, specialized memory systems. This predicts that VWM capacity will be subject to independent limits for movements and object properties because the movements and object properties would be retained in separate buffers. To distinguish between these possibilities, in Experiment 2 participants performed the movement and object property memory tasks concurrently and separately.

Experiment 2

Performance in concurrent memory tasks reveals how the tasks compete for memory resources. When two tasks do not compete for resources, performance on one task should not suffer when the other task is performed concurrently. When two tasks do compete for resources, performance on one or both of the tasks will suffer when the other task is also being performed. If movement information and object property information are retained in the same VWM system, then observers will retain a significantly smaller number of items when the tasks are performed concurrently compared to separately because the movements and object properties will compete for the limited storage resources of a single VWM system. However, if movement information and object property information are retained in separate VWM systems, then observers will retain a similar number of items whether the tasks are performed concurrently or separately because the movements and object properties will not compete for the limited storage resources of a single VWM system.

Method

Ten new participants (male: 3, female: 7; mean age = 21.9 years, $SD = 4.04$) participated. Experiment 2 was identical to Experiment 1 except in the following ways. First, in both the movement memory task and the object property memory task, participants were presented with three to-be-remembered items. Experiment 1 showed that three movements and three colors is sufficient to deplete the available VWM storage resources for sequentially presented movements and colors. Second, participants completed four conditions, each of which contained 50 trials. The order of conditions was counterbalanced across participants. In the

'movement task' condition, participants performed the movement memory task alone. In the 'object property task' condition, participants performed the object property memory task alone. In the 'movement task and object property task' conditions, participants performed the movement memory task and the object property memory task concurrently. In one movement task and object property task condition the movements were presented first, and in the other movement task and object property task condition the color changes were presented first. Third, the delay interval before the presentation of the test item was increased in the movement task condition and the object property task condition so that participants needed to retain information about the first to-be-remembered item for an equal duration across all conditions. Fourth, the color changes were presented as changes to the figure's clothing so that all of the to-be-remembered items could be presented on a single enduring object. See Figure 2A for a schematic illustration of a trial from each condition. During each trial, participants performed an articulatory suppression task to prevent verbal recoding of the stimuli.

Results and Discussion

Figures 2B and 2C illustrate the results from Experiment 2 (see Appendix 2B in the online supplementary materials for the hits and false alarms for all conditions). Participants could remember similar numbers of movements and object properties when they performed the memory tasks concurrently and separately. Participants remembered 2.11 movements when they performed the movement memory task alone and 2.03 movements when they performed the task concurrently with the object property memory task ($F(1, 9) = .63, p = .45, h_p^2 = .07$), and 2.64 colors when they performed the object property memory task alone and 2.25 colors when they performed the task concurrently with the movement memory task ($F(1, 9) = 15.12, p = .004, h_p^2 = .63$). Thus, when participants performed a movement memory task and an object property memory task concurrently, there was little to no interference between the tasks for the limited storage resources of a single VWM system. This suggests that spatiotemporally defined movement information and object color property information are retained in separate VWM systems. Convergent evidence for this conclusion comes from Wood (2008), in which there was no competition between memory for colors and memory for movements for the limited storage resources of a single VWM system.

Overall, participants remembered a total of 4.27 items when they performed the memory tasks concurrently and 4.75 items when they performed the tasks separately. This decline was sta-

Figure 2 (opposite). (A) Flow chart of events for the dual-task paradigm used in Experiment 2. In the movement task condition, participants attempted to remember 3 movements. In the object property task condition, participants attempted to remember 3 color changes. In the movement task & object property task conditions, participants attempted to remember 3 movements and 3 color changes concurrently. (B, left): Predictions of a VWM architecture in which movements and color properties are retained in the same buffer and therefore compete with one another for the limited storage resources of a single working memory mechanism. (B, middle): Predictions of a VWM architecture in which movements and color properties are retained in separate buffers and therefore do not compete with one another for the limited storage resources of a single working memory mechanism. (B, right): Results of Experiment 2 showing the storage capacities for movements and color properties. (C, left): Predictions of the total number of items that can be retained within a VWM architecture in which movements and color properties are retained in the same buffer. (C, middle): Predictions of the total number of items that can be retained within a VWM architecture in which movements and color properties are retained in separate buffers. (C, right): Results of Experiment 2 showing the total number of items that could be retained. Error bars represent *SE*.

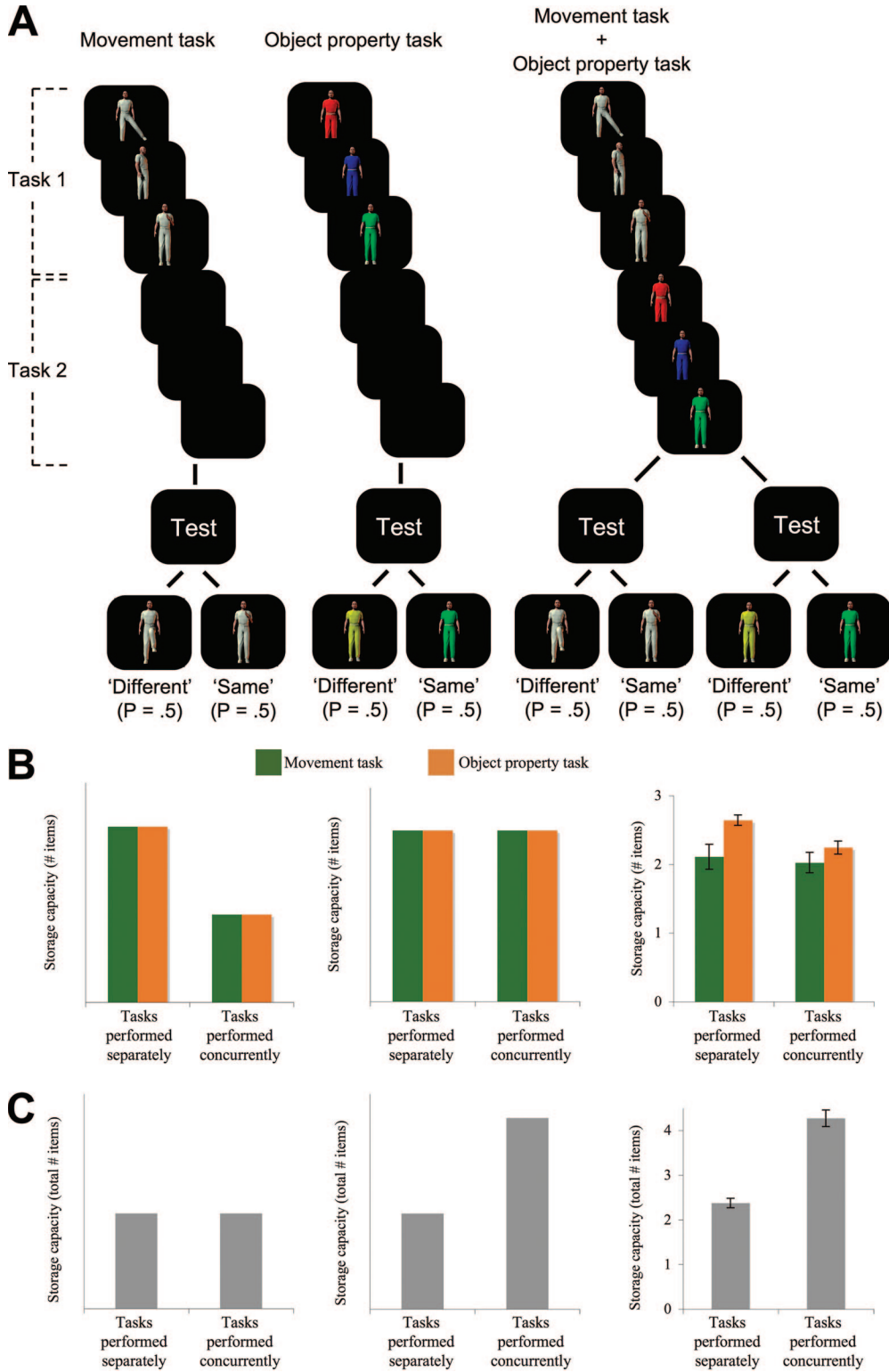


Figure 2 (opposite).

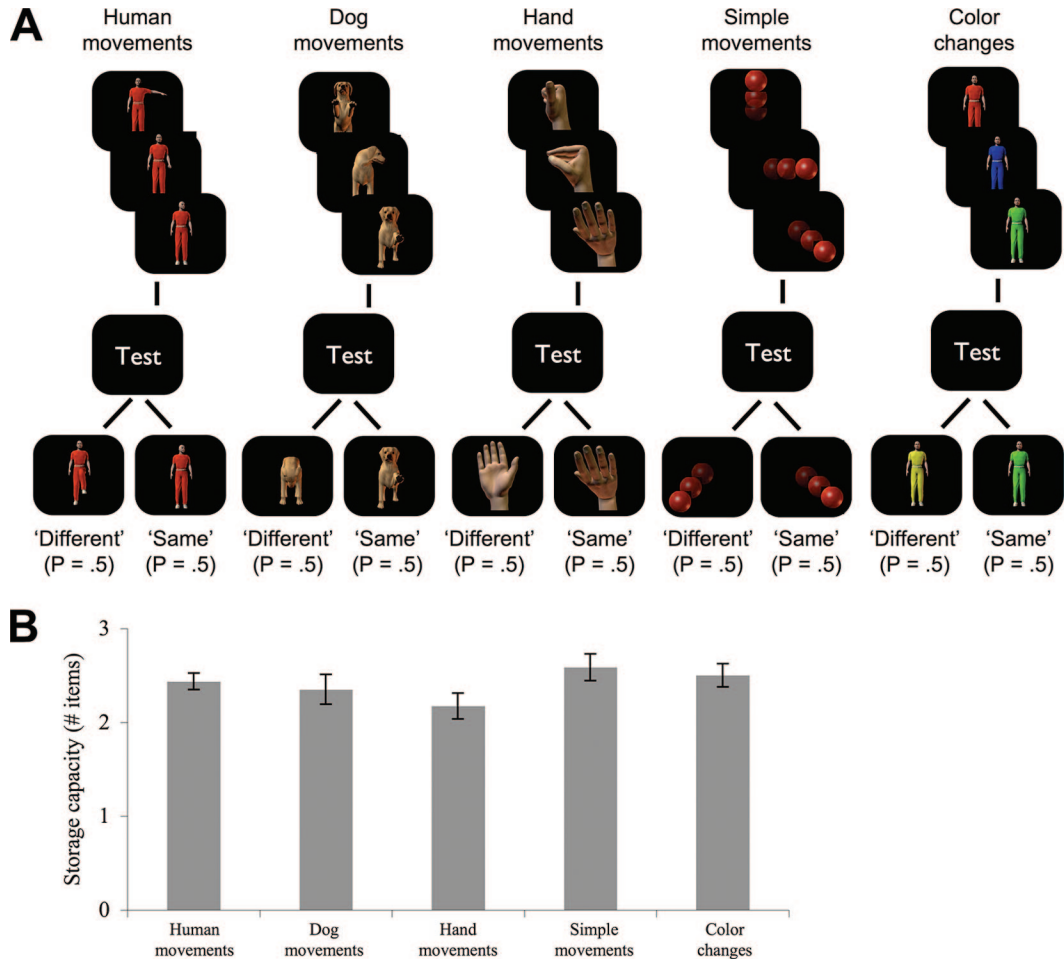


Figure 3. (A) Flow chart of events for Experiment 3a, in which participants attempted to remember human movements, dog movements, hand movements, simple movements, and color changes. (B) Average number of items that could be retained at once in Experiment 3a. (C) Flow chart of events for Experiment 3b, in which participants attempted to remember human movements in one memory task and human movements, dog movements, hand movements, simple movements, and color changes in the other memory task. The test items depict 'different trials' only. (D) Average dual-task interference for each of the conditions in Experiment 3b. Red bars indicate significant competition for storage resources between the events in the first and second memory tasks. Error bars represent *SE*.

tistically significant, $F(1, 9) = 6.25$, $p = .03$, $h_p^2 = .41$. However, this dual-task cost was small, 0.48 item's worth of information, and is no greater than the 0.60–0.80 item cost observed in previous dual-task experiments that placed high loads on two different working memory systems concurrently (i.e., verbal working memory and VWM; Morey & Cowan, 2004). Such dual-task costs can be attributed to a more central, amodal component of working memory (see Fougny & Marois, 2006).

Experiment 3

The core knowledge architecture predicts that the VWM system that retains information about human movements will also retain information about other spatiotemporal events. To test this prediction, I conducted two additional experiments. In Experiment 3a, participants attempted to remember a wide range of events, including color changes and different types of spatiotemporally defined

movements. Specifically, participants attempted to remember (1) human movements, (2) nonhuman animal movements, (3) hand movements, (4) simple movements (horizontal, vertical, diagonal) performed by a 3D sphere, and (5) color changes (see Figure 3A). This experiment established the storage capacities of VWM for these different event categories.

In Experiment 3b, I examined whether these different types of events compete with one another for the limited storage resources of a single VWM system. Specifically, participants performed two memory tasks concurrently (see Figure 3B). In one memory task, participants attempted to remember three human movements. In the other memory task, participants attempted to remember three events from one of the five event categories listed above.

If observers retain information about these different events in the same VWM system, then the storage capacities will be lower in Experiment 3b, when the memory tasks are performed concu-

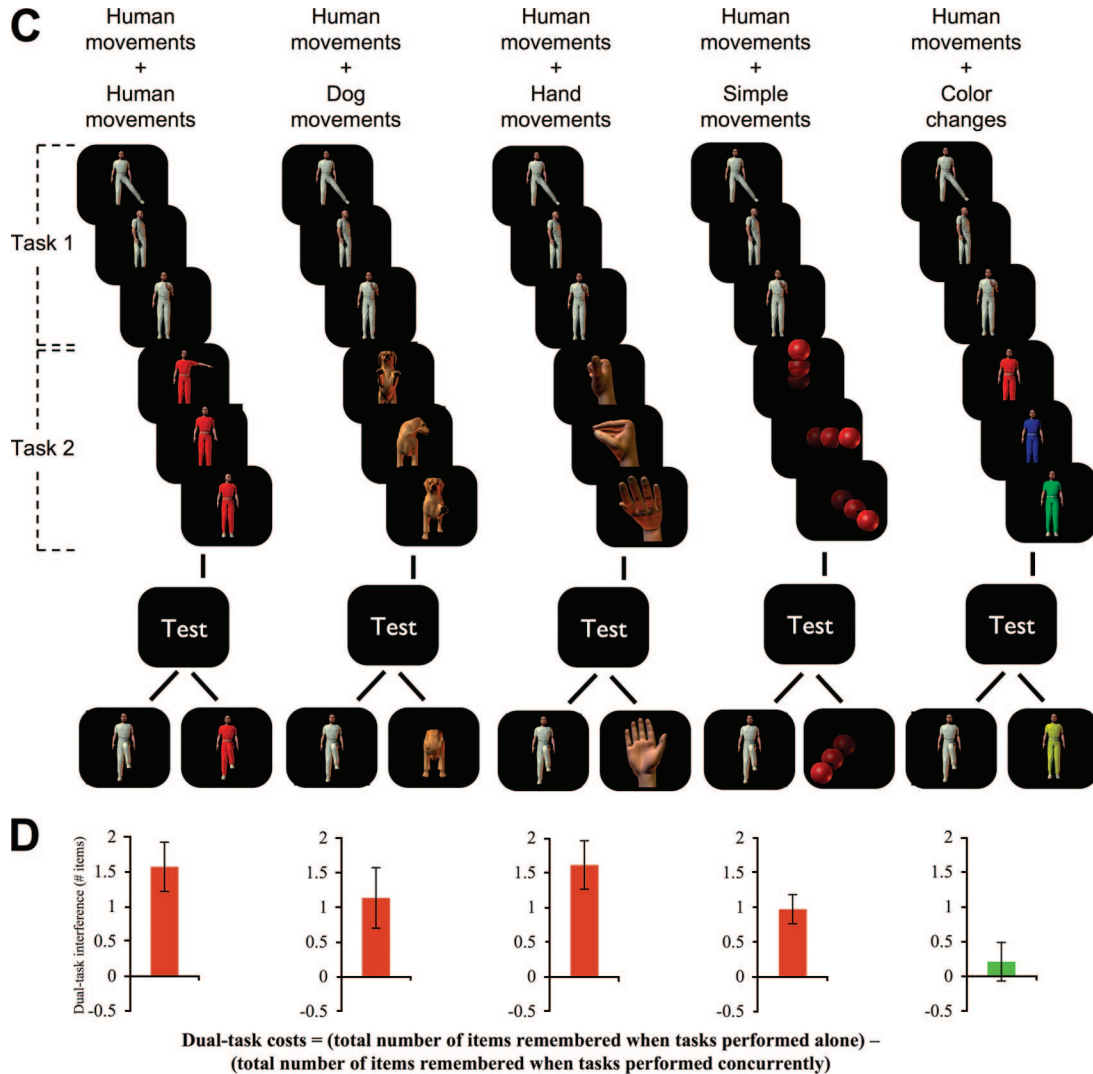


Figure 3 (continued).

rently, than in Experiment 3a, when the memory tasks are performed separately. However, if observers retain information about these different events in separate, specialized memory systems, then the storage capacities will be similar whether the memory tasks are performed concurrently, as in Experiment 3b, or separately, as in Experiment 3a.

Method

Ten new participants took part in each experiment: Experiment 3a (male: 5, female: 5; mean age = 21.2 years, $SD = 3.16$) and Experiment 3b (male: 2, female: 8; mean age = 21.8 years, $SD = 2.82$). The methods were identical to those used in Experiments 1–2 except in the following ways. On each trial two computer-generated objects were visible, positioned to the left and right of the center of the screen. One of the objects was the human figure used in Experiments 1–2. The other object was the figure from one of the five event categories described below. In the test event, one of the two figures performed a single movement or change, and

participants indicated whether that movement or change had occurred in the trial. An arrow appeared at the center of the screen before the test event to direct the participant's attention to the appropriate test figure.

In Experiment 3a, participants needed to remember three movements or changes, which were performed by one of the figures on the screen. All three events were drawn from the same event category. Specifically, in separate blocks, each of which consisted of 50 trials (preceded by six practice trials), participants tried to remember three movements or changes from the following event categories:

1. Human movements: These movements were identical to those used in Experiments 1 and 2 (see Appendix 3A in the online supplementary materials).
2. Dog movements: These movements were performed by a computer-animated dog, which subtended $3 \times 6^\circ$ on the computer monitor. The movements were selected at random

from a set of six highly discriminable movements (see Appendix 3A in the online supplementary materials).

3. Human hand movements: These movements were performed by a computer-animated hand, which subtended $4 \times 7.5^\circ$ on the computer monitor. The movements were selected at random from a set of six highly discriminable movements (see Appendix 3A in the online supplementary materials).
4. Simple movements of a 3D sphere: The 3D sphere subtended $3.5 \times 3.5^\circ$ on the computer monitor. The movements were selected at random from a set of eight highly discriminable movements: left, right, up, down, up-left, up-right, down-left, and down-right (see Appendix 3A in the online supplementary materials).
5. Color changes: These changes were identical to those used in Experiment 2 (see Appendix 3A in the online supplementary materials).

In Experiment 3b, participants tried to remember six events, three of which were movements performed by the human figure and three of which were performed by the other figure on the screen. Thus, participants performed two memory tasks, attempting to remember three human movements in the first memory task and three events from one of the five event categories in the second memory task. On 50% of the trials, the human movements were presented first, and on the other 50% of the trials, the other events were presented first. During each trial, participants performed an articulatory suppression task to prevent verbal recoding of the stimuli.

To determine whether the participants in Experiments 3a and 3b had similar memory capacities, participants in Experiment 3a also performed a sixth condition that was identical to the condition in Experiment 3b that required memory for six human movements (three movements that were performed by the figure on the left side of the screen and three movements that were performed by the figure on the right side of the screen).

Results and Discussion

Participants in Experiments 3a and 3b could remember nearly identical numbers of movements in the condition that required memory for six human movements (3.15 and 3.30 movements, respectively), $F(1, 18) = 0.14$, $p = .72$, $h_p^2 = .01$. Thus, there was not a significant difference between the memory capacities of the subjects in Experiments 3a and 3b.

Figures 3B and 3D depict the results (see Appendix 3B in the online supplementary materials for the hits and false alarms for all conditions). The results from Experiment 3a show that participants could remember 2–3 items from each event category: 2.25 human movements, 2.31 dog movements, 2.09 hand movements, 2.56 simple directional movements, and 2.39 color changes. A comparison of the storage capacities between Experiments 3a and 3b revealed little to no interference between the memory tasks when participants were retaining human movements in one memory task and color changes in the other memory task. Participants remembered nearly the same number of items from each event category in Experiment 3b, when they needed to remember the movements

and color properties concurrently, and in Experiment 3a, when they remembered the movements and color properties separately, $F(1, 18) = 0.66$, $p = .43$, $h_p^2 = .04$. Thus, the number of movements that can be retained in VWM is independent of the number of color properties also being retained, and the number of color properties that can be retained is independent of the number of movements also being retained. This replicates the main finding from Experiment 2 in a between-subjects design, thereby providing further evidence that spatiotemporal information and object property information are retained in separate VWM systems.

In contrast, there was significant interference between memory for human movements and memory for all other spatiotemporally defined movements. Participants remembered fewer movements in Experiment 3b, when they needed to remember movements in two concurrently performed memory tasks, compared to in Experiment 3a, when they remembered movements in two memory tasks that were performed separately. Specifically, there was significant interference between memory for human movements and memory for movements performed by another human ($F(1, 18) = 22.18$, $p < .001$, $h_p^2 = .55$), a dog ($F(1, 18) = 7.72$, $p = .01$, $h_p^2 = .30$), a human hand ($F(1, 18) = 17.48$, $p < .001$, $h_p^2 = .49$), and a 3D sphere ($F(1, 18) = 7.98$, $p = .01$, $h_p^2 = .31$). This pattern of dual-task interference, in which competition was observed between memory for human movements and memory for all tested movements, suggests that observers retain information about a wide range of movements within a single VWM system that is dedicated for spatiotemporal information.

Experiment 4

Two types of evidence suggest that spatiotemporal information and object property information are retained in separate VWM systems. First, spatiotemporal information and object property information are subject to independent storage limits, as shown in Experiments 2–3 (see also Wood, 2008). Second, when observers retain information about the properties of objects and the movements of objects, they make a significant number of binding errors, failing to remember which objects performed which movements (Wood, 2008). Thus far, these property-movement binding errors have been demonstrated only when observers retain information about human figures and their movements. Experiment 4 examined whether property-movement binding errors also occur when observers retain information about other types of objects and their movements.

On each trial, participants viewed a study sequence consisting of three sequentially presented 3D ring-shaped figures, each of which performed a movement. The rings differed from one another in color. After a brief delay, a test ring appeared and performed a movement, and participants indicated, in separate conditions, whether the test ring, the test movement, the test ring or the test movement, or the test ring-movement combination had been present in the study sequence.

Method

Participants. Eight participants (male: 2, female: 6; mean age = 21.6 years, SD = 3.07) took part.

Design. On each trial, participants viewed a study sequence consisting of three different computer-animated ring-shaped fig-

ures, each of which performed a movement. After a brief delay interval, a test ring appeared and performed a movement, and participants indicated whether the relevant test display information had been present in the study sequence, with respect to the following conditions:

1. **Object properties only:** Participants were told that only the ring colors could change and to remember only these properties. On different trials, the test display presented a ring that was a different color from the rings in the study sequence; this new ring performed a movement that one of the rings from the study sequence had performed.
2. **Movements only:** Participants were told that only the movements could change and to remember only the movements. On different trials, the test display presented a movement that had not been performed in the study sequence; this movement was performed by one of the rings from the study sequence.
3. **Both object properties and movements:** Participants were told that either the ring colors or the movements could change and to remember both the color properties and the movements. On 50% of the different trials, the test display presented a ring that was a different color from all of the rings in the study sequence. On the other 50% of the different trials, the test display presented a movement that had not been performed in the study sequence.
4. **Binding object properties and movements:** The test display always contained a ring and a movement that had been present in the study sequence. However, on different trials, the test ring performed a movement that had been performed by one of the other rings in the study sequence. Participants were told to treat such changes as different.

Participants received 50 trials in each condition, each of which was preceded by six practice trials. The order of conditions was counterbalanced across participants.

Procedure. Each trial began with a 1,000-ms presentation of two randomly selected letters, and participants were required to repeat those letters continuously and out loud until the end of the trial. Thus, during each trial, participants performed an articulatory suppression task to prevent verbal recoding of the stimuli. The offset of these letters was followed by a 1,000-ms presentation of a screen displaying the word “ready,” followed by the presentation of the study sequence. The study sequences consisted of three different sequentially presented 3D rings, each of which performed a different movement. The rings subtended $4.5 \times 4.5^\circ$ at the center of the monitor. The rings differed in color, which were picked at random without replacement from a set of seven highly discriminable colors (red, orange, yellow, green, blue, white, and purple). After appearing, each ring performed a movement, which lasted 500 ms and was followed by 500 ms of stasis. All movements were dynamic (i.e., they involved fluid, continuous change, rather than being presented as static pictures). Then, the ring was replaced with a new ring (see Figure 4A). The movements were selected at random without replacement from a set of seven highly discrim-

inable movements (see Appendix 4A in the online supplementary materials).

The study sequence was followed, after a 500-ms delay interval, by a 1,000-ms presentation of the word “test,” followed by the presentation of the test display, which consisted of a single ring performing a movement. Participants were required to make a response to the test event, indicating whether the relevant test display information had been present in the study sequence.

Results and Discussion

Figure 4B depicts the results (see Appendix 4B in the online supplementary materials for the hits and false alarms for all conditions). A repeated measures ANOVA revealed a main effect of condition, $F(3, 21) = 11.72, p < .001, h_p^2 = .63$. Memory capacity was nearly significantly lower in the *movements only* condition (2.10 movements) than the *object properties only* condition (2.73 colors), $t(7) = 2.11, p = .07$. Memory capacity in the *both* condition for the movements (1.84 movements) and the object properties (2.32 colors) did not differ significantly from the memory capacities in the *object properties only* and *movements only* conditions, respectively: object property comparison: $t(7) = 1.82, p = .11$; movement comparison: $t(7) = 1.39, p = .21$. Thus, memory for object color properties did not interfere with memory for movements, and memory for movements did not interfere with memory for object color properties. However, memory capacity was significantly lower in the *binding* condition (1.29 integrated representations), when participants needed to remember which color properties occurred with which movements, than in the *both* condition, when participants needed to remember the same number of color properties and movements but in a nonintegrated form, $t(7) = 3.80, p = .007$. The memory capacity in the *binding* condition differed significantly from the memory capacities in the *both* condition for the color properties, $t(7) = 4.24, p = .004$ and the movements, $t(7) = 2.80, p = .03$. Thus, despite the fact that performance in the *both* condition shows that it is possible to retain information about multiple color properties and movements simultaneously, these different types of information are not necessarily retained as integrated representations in VWM. Rather, they are stored in separate VWM systems. This pattern of results mirrors that obtained when observers attempt to remember human figures and their movements (Wood, 2008). Thus, property-movement binding errors appear to occur for a range of objects and observed movements.

An alternative explanation for the findings in Experiments 1–4 is that participants used separate, specialized VWM systems for representing shape and color information rather than separate, specialized systems for representing spatiotemporal and object-based property information. Specifically, when objects move their shape often changes as well; for example, when a human figure raises his arm, the shape of his body changes between the start of the movement and the end of the movement. If movement information and shape information are stored in the same VWM system, then these two types of information should compete with one another for the limited storage resources of that system. Experiment 5 tested this prediction.

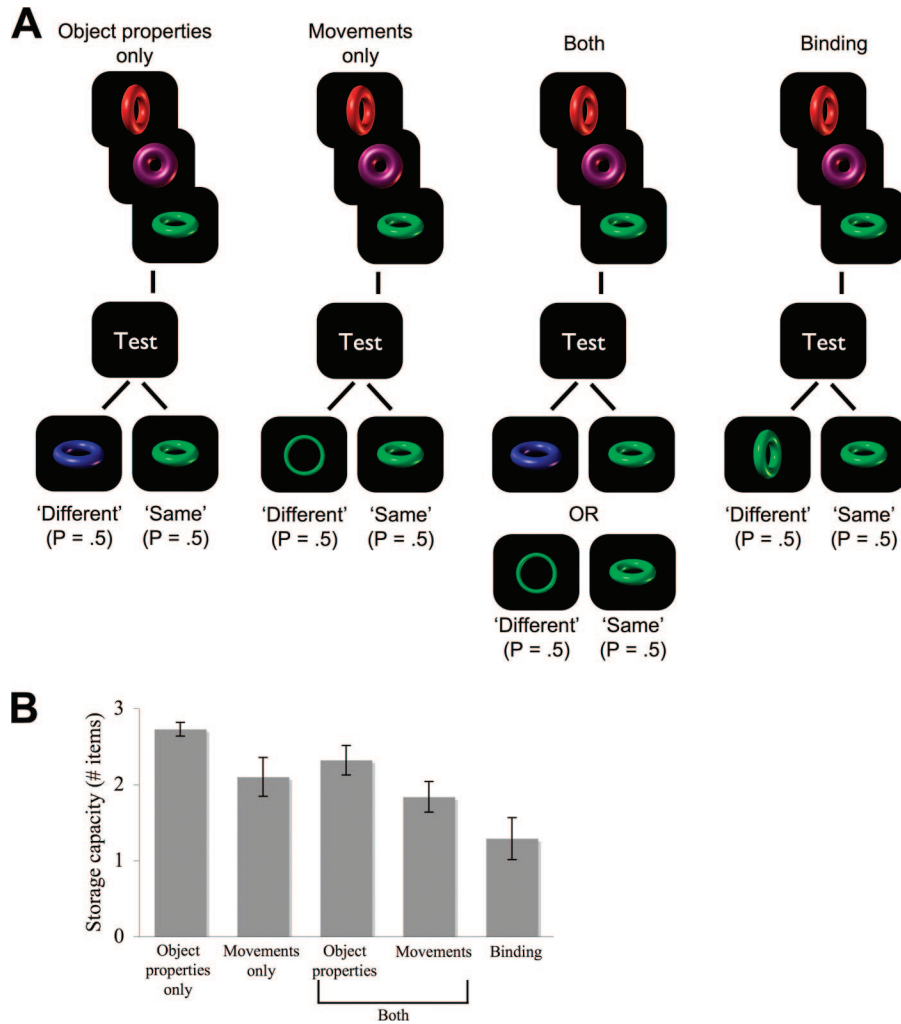


Figure 4. (A) Flow chart of events for Experiment 4, in which participants attempted to remember object color properties only, movements only, object color properties and movements, and which object color properties occurred with which movements. (B) Average number of items that could be retained at once in each condition. Error bars represent *SE*.

Experiment 5

Experiment 5 examined whether movement and shape information are stored together or separately in VWM by using the dual-task paradigm. In the first memory task, participants attempted to remember 0–3 movements. In the second memory task, participants attempted to remember 0–6 shapes. If information about movements and shapes are retained in the same VWM system, then participants should retain a significantly smaller number of items when the tasks are performed concurrently compared to separately because the movement and shape information will compete for the limited storage resources of a single VWM system. However, if information about movements and shapes are retained in separate VWM systems, then participants should retain a similar number of items whether the tasks are performed concurrently or separately because the movement and shape information will not compete for limited VWM storage resources.

Method

Ten new participants (male: 5, female: 5; mean age = 19.9 years, $SD = 1.60$) participated. Each trial began with the articulatory suppression task described in Experiment 1. The offset of these letters was followed by a 1,000-ms presentation of a screen displaying the word *ready*, followed by the presentation of the items in the first memory task within a movement sequence. The movement sequences consisted of 0–3 movements performed by the computer-generated human figure used in Experiments 1–3. The movement sequence was followed, after a 500-ms delay interval, by the second memory task, which consisted of 0, 2, 4, or 6 white shapes (see Appendix 5A in the online supplementary materials) presented in an array on a black background. In the 2-object arrays, the shapes ($1.75 \times 2^\circ$) were presented on the horizontal mid line, offset 3.5° from the center of the screen. In the four-object arrays, the shapes were presented equidistant from the

middle of the screen in four quadrants, offset 3.5° from the vertical midline and 1.5° from the horizontal midline. In the six-object arrays, two shapes were presented on the horizontal midline, offset 3.5° from the middle of the screen, and the remaining four shapes were offset 3° above and below those objects. After a 500-ms delay interval, there was a 1,000-ms presentation of the word test, followed by the presentation of the test item. The test item consisted of a single movement (50% of trials) or shape (50% of trials) presented at the center of the screen. Participants indicated whether that test item had been present in the trial, which was the case on 50% of the trials. Participants received 24 trials for each unique set size combination of movements and shapes (with the exception that there were no trials with 0 movements and 0 shapes). See Figure 5A for a schematic illustration of a trial.

Results and Discussion

Figure 5B depicts the results (see Appendix 5B in the online supplementary materials for the hits and false alarms for all conditions). Participants could remember the same number of movements in the first memory task independent of the number of shapes (0, 2, 4, 6) that they remembered from the second memory task, $F(3, 27) = 1.03, p = .40; h_p^2 = .10$. Thus, the number of movements that could be retained at once did not vary as a function of the number of shapes also being retained.

Similarly, the number of shapes that participants could remember from the second memory task was nearly independent of the

number of movements (0, 1, 2, 3) that they remembered from the first memory task, $F(3, 27) = 2.80, p = .06; h_p^2 = .24$. There was a nearly significant effect of the load of the movement memory task on the shape memory task, but this effect did not increase as the number of movements that were represented in the first memory task increased (see Figure 5B). This is not the pattern of dual-task interference one should expect if movement and shape information were stored in the same VWM system (and thus competed for limited VWM storage resources). If these two types of information had competed, then the number of shapes that could be remembered in the second memory task should have declined when participants retained a greater number of movements in the first memory task. Further, the dual-task cost of 0.36 item's worth of information is no greater than the 0.60-0.80 item cost observed in previous dual-task experiments that placed high loads on two different working memory systems concurrently (i.e., verbal working memory and VWM; Morey & Cowan, 2004). Such dual-task costs can be attributed to a more central, amodal component of working memory (see Fougnie & Marois, 2006).

When participants tried to remember movements and shapes concurrently, the number of movements that could be retained at once did not vary as a function of the number of shapes also being retained, and the number of shapes that could be retained at once was similar regardless of the number of movements also being retained. Thus, information about movements and shapes do not compete for the limited storage resources of a single VWM system.

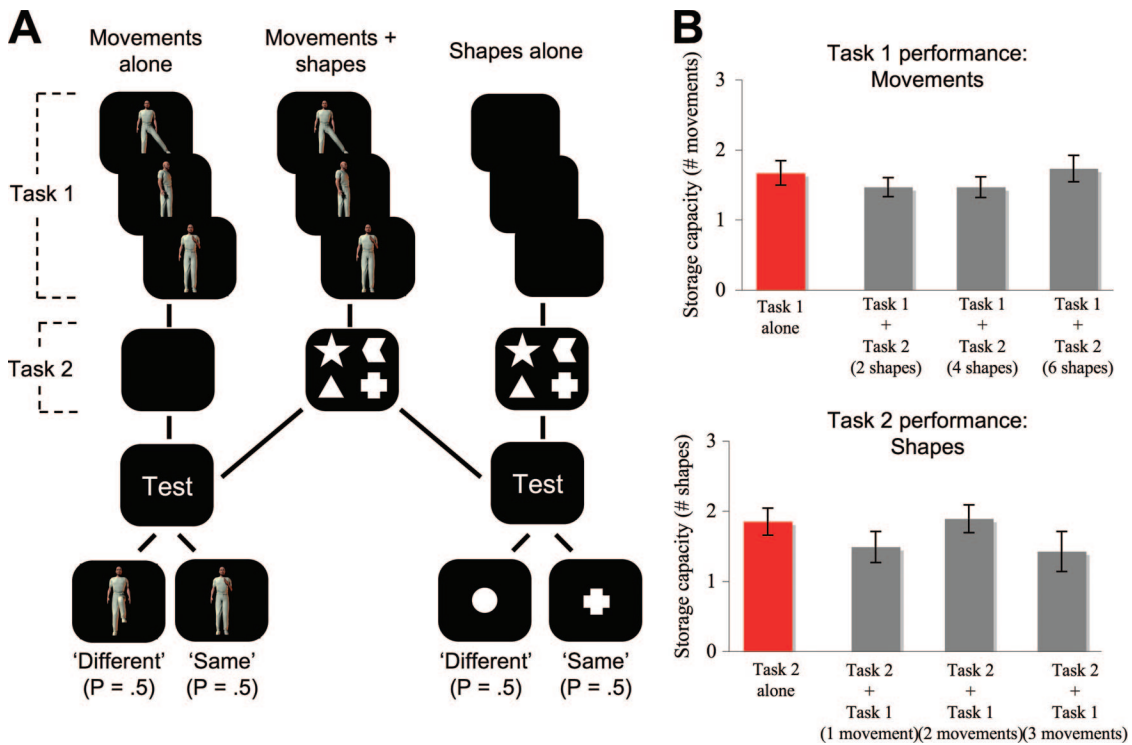


Figure 5. (A) Flow chart of events for the dual-task paradigm used in Experiment 5. In the first memory task, participants attempted to remember 0-3 movements. In the second memory task, participants attempted to remember 0, 2, 4, or 6 shapes. (B) Results of Experiment 5. Red bars indicate trials in which the memory tasks were performed alone and grey bars indicate trials in which the memory tasks were performed concurrently. Error bars represent SE.

Experiments 1–5 provide evidence that spatiotemporal information and object property information are retained in separate VWM systems. Experiments 1–3 show that spatiotemporal information and object color information are subject to independent storage limits, and Experiment 4 shows that when observers retain movement and object color information, they make a significant number of binding errors, failing to remember which colors occurred with which movements. Finally, Experiment 5 shows that these results cannot be explained by appealing to separate, specialized VWM systems for shape and color information because there is little to no competition between these two types of information for VWM storage resources. Importantly, these VWM systems for spatiotemporal information and object property information retain the types of information that are used by the core knowledge systems that underlie object tracking and object property/kind representation, respectively.

As discussed in the introduction, there is also a third core knowledge system that stores view-dependent snapshot representations. Which VWM system retains this snapshot information? Snapshot information might be retained in either the VWM system that retains object property information or the VWM system that retains spatiotemporal information. Alternatively, studies of nonhuman animals and human infants suggest that snapshot information is retained in a separate, specialized memory system.

To distinguish between these possibilities, Experiment 6 examined whether spatiotemporal-based and snapshot-based information are stored together or separately in VWM, and Experiments 7–8 examined whether object-based and snapshot-based information are stored together or separately in VWM. To be clear, these experiments were not designed to test whether snapshot-based representations are view-dependent (see Wood, 2009, for experiments that specifically examined the view-dependence of VWM representations).

Experiment 6

Experiment 6 examined whether spatiotemporal and snapshot-based information are stored together or separately in VWM by using the dual-task paradigm. Wood (2007) showed that information about spatiotemporally defined movements and information about color features in a scene are subject to independent working memory storage limits, which indicates that these different types of information are retained in separate VWM systems. This study replicates this finding with a new group of subjects.

In the first memory task, participants attempted to remember 0–3 movements. In the second memory task, participants attempted to remember 0–6 colored squares presented simultaneously in a scene. If information about movements and color features in a scene are retained in the same VWM system, then participants should retain a significantly smaller number of items when the tasks are performed concurrently compared to separately because the movement and scene information would compete for the limited storage resources of a single VWM system. However, if information about movements and color features in a scene are retained in separate VWM systems, then participants should retain a similar number of items whether the tasks are performed concurrently or separately because the movement and scene information would not compete for limited working memory storage resources.

Method

Ten new participants (male: 4, female: 6; mean age = 20.2 years, $SD = 1.99$) participated. The methods were identical to those used in Experiment 5 except the objects in the second memory task consisted of highly distinctive colored squares (red, orange, yellow, green, blue, white, purple; see Appendix 6A in the online supplementary materials). During each trial, participants performed an articulatory suppression task to prevent verbal recoding of the stimuli. See Figure 6A for a schematic illustration of a trial.

Results

Figure 6B depicts the results (see Appendix 6B in the online supplementary materials for the hits and false alarms for all conditions). Participants could remember nearly the same number of movements in the first memory task independent of the number of colored squares that they remembered from the scene in the second memory task, $F(3, 27) = 0.64$, $p = .60$; $h_p^2 = .07$, and participants could remember nearly the same number of colored squares from the scene in the second memory task independent of the number of movements that they remembered from the first memory task, $F(3, 27) = 0.64$, $p = .60$; $h_p^2 = .07$.

Discussion

When participants tried to remember movements and colored squares in a scene concurrently, the number of movements that could be retained at once did not vary as a function of the number of colored squares also being retained, and the number of colored squares that could be retained at once did not vary as a function of the number of movements also being retained. Thus, information about movements and color features in a scene do not compete for the limited storage resources of a single working memory system. This indicates that spatiotemporal information and information about color features in a scene are retained in separate VWM systems. This experiment replicates the finding reported by Wood (2007).

Experiment 7

Experiment 7 examined whether information about object-based color properties and information about snapshot-based color features are retained together or separately in VWM by using the dual-task paradigm. In the first memory task, participants attempted to remember 0–3 color changes presented on a single 3D object (as in Experiment 1). In the second memory task, participants attempted to remember 0–6 colored squares presented in a scene (as in Experiment 6). If object-based color properties and snapshot-based color features are retained in the same VWM system, then participants should retain a significantly smaller number of items when the tasks are performed concurrently compared to separately because the object-based color information and the snapshot-based color information will compete for the limited storage resources of a single VWM system. However, if object-based color information and snapshot-based color information are retained in separate VWM systems, then participants should retain a similar number of items whether the tasks are performed concurrently or separately because the object-based color information

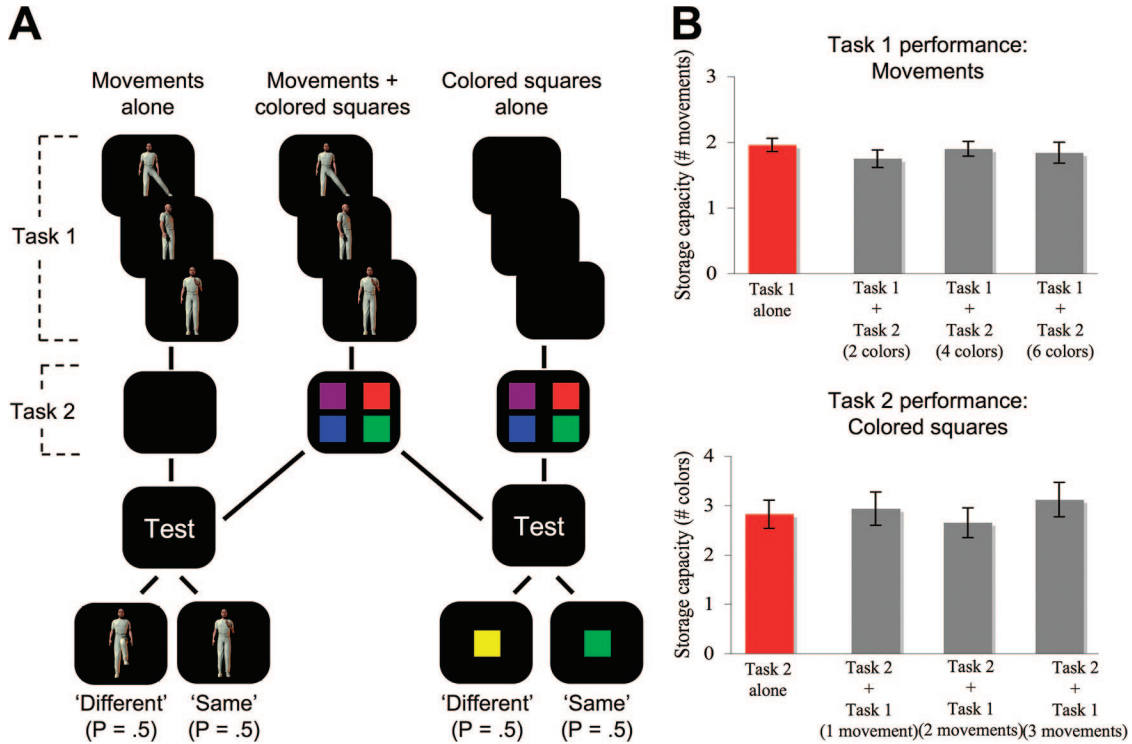


Figure 6. (A) Flow chart of events for the dual-task paradigm used in Experiment 6. In the first memory task, participants attempted to remember 0-3 movements. In the second memory task, participants attempted to remember 0, 2, 4, or 6 colored squares presented in a scene. (B) Results of Experiment 6. Red bars indicate trials in which the memory tasks were performed alone and grey bars indicate trials in which the memory tasks were performed concurrently. Error bars represent *SE*.

and the snapshot-based color information will not compete for limited VWM storage resources.

This experiment provides an especially critical and counterintuitive test of the core knowledge architecture. The core knowledge architecture predicts that properties of individual objects and features within a view-dependent snapshot will be stored in separate VWM systems. This independence between object-based and snapshot-based information should hold even when the to-be-remembered information in both memory tasks are drawn from the same feature dimension of color. Color features can be stored within a view-dependent snapshot representation (Gillner et al., 2008), and color features can be properties of an individual object (Hollingworth & Rasmussen, 2010). Thus, if VWM contains separate systems for view-dependent snapshot information and object-based information, then it should be possible to retain color information in the object-based system while concurrently retaining color information in the snapshot-based system. In contrast, other proposed architectures of VWM, such as the spatial-object architecture, do not predict that object-based and snapshot-based information will be stored in separate memory systems because these architectures do not distinguish between object-based and snapshot-based information. Thus, these architectures must predict that object-based and snapshot-based information will be retained in the same VWM system, thereby leading to significant interference between the two memory tasks.

Method

Seventeen new participants (male: 6, female: 11; mean age = 20.6 years, $SD = 3.06$) participated. The methods were identical to those used in Experiment 6 except the movements in the first memory task were replaced with color changes (identical to those used in Experiment 1). During each trial, participants performed an articulatory suppression task to prevent verbal recoding of the stimuli. See Figure 7A for a schematic illustration of a trial.

Results

Figure 7B depicts the results (see Appendix 7B in the online supplementary materials for the hits and false alarms for all conditions). Participants could remember nearly the same number of color changes in the first memory task independent of the number of colored squares (2, 4, 6 objects) that they remembered from the second memory task, $F(2, 32) = 0.13, p = .88; h_p^2 = .01$. The only sign of interference between the two tasks was a slight decline in performance in the first memory task when observers also performed the second memory task, $F(1, 16) = 9.45, p = .007; h_p^2 = .37$. However, this effect was small, 0.34 color's worth of information, and did not increase as the memory demands on the second memory task increased. Further, the magnitude of this dual-task cost was no greater than the 0.60-0.80 item cost observed in

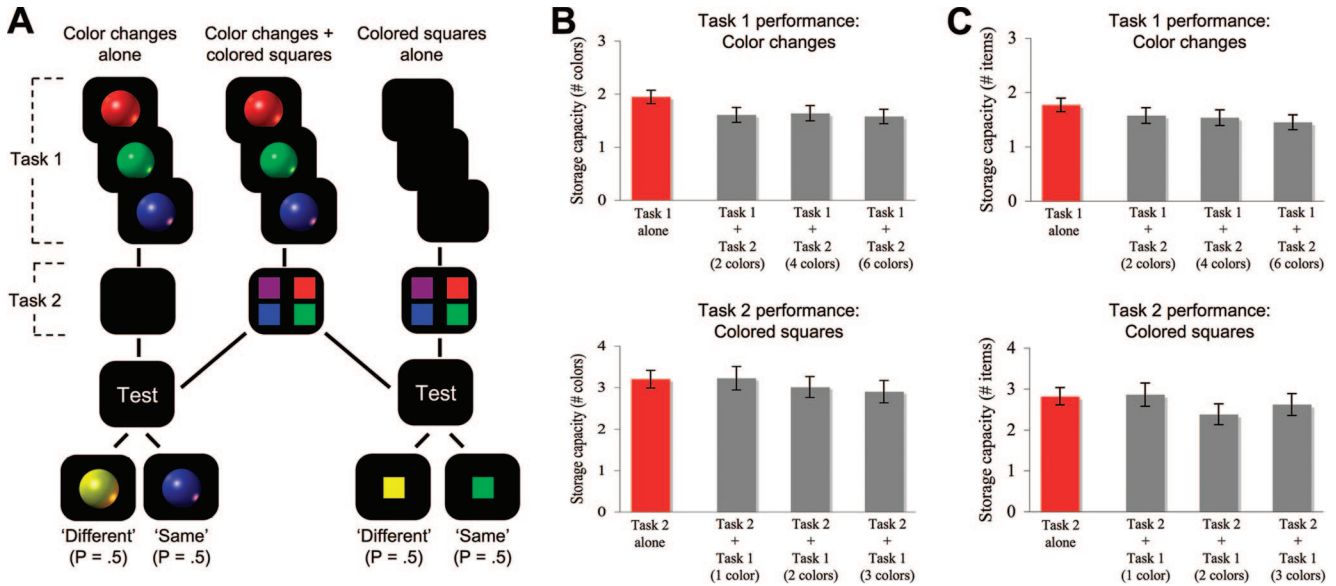


Figure 7. (A) Flow chart of events for the dual-task paradigm used in Experiments 7–8. In the first memory task, participants attempted to remember 0–3 color changes. In the second memory task, participants attempted to remember 0, 2, 4, or 6 colored squares presented in a scene. (B) Results of Experiment 7. (C) Results of Experiment 8. Red bars indicate trials in which the memory tasks were performed alone and grey bars indicate trials in which the memory tasks were performed concurrently. Error bars represent *SE*.

previous dual-task experiments that placed high loads on two independent working memory systems concurrently (Morey & Cowan, 2004).

Results also showed that participants could remember the same number of colored squares from the scene in the second memory task independent of the number of color changes (0, 1, 2, 3 changes) that they remembered from the first memory task, $F(3, 48) = 0.72$, $p = .55$; $h_p^2 = .04$.

Discussion

Color information can be part of a representation of an individual object or part of a snapshot representation of the scene. This experiment examined whether object-based color information and snapshot-based color information are retained in the same VWM system or in separate systems. In a dual-task experiment, when participants attempted to remember color changes occurring to a 3D object in the first memory task and color features in a scene in the second memory task, the number of color changes that could be retained from the first memory task did not vary as a function of the number of color features also being retained from the second memory task, and the number of color features that could be retained from the second memory task did not vary as a function of the number of color changes also being retained from the first memory task. Thus, the color information used for the first memory task and the color information used for the second memory task did not compete with one another for the limited storage resources of a single VWM system. Rather, they were stored in separate VWM systems.

This experiment confirms a counterintuitive prediction of the core knowledge architecture. Information from the same feature dimension of color can be retained in parallel within two separate, specialized VWM systems. As described in the introduction, Hol-

lingworth and Rasmussen (2010) provide convergent evidence that separate object-based and scene-based components of VWM retain color information. To test the reliability of this finding, however, I conducted a final experiment that attempted to replicate this result with a new group of participants.

Experiment 8

Experiment 8 was identical to Experiment 7.

Method

Ten participants (male: 3; female: 7) between the ages of 18 and 22 ($M = 20.2$, $SD = 1.32$) served. The methods were identical to those used in Experiment 7.

Results

Figure 7C depicts the results. Participants were able to remember the same number of color changes in the first memory task irrespective of the number of color features (0, 2, 4, 6 colored squares) remembered from the second memory task, $F(3, 27) = 1.17$, $p = .34$; $h_p^2 = .12$. Similarly, participants were able to remember the same number of color features in the second memory task irrespective of the number of color changes (0, 1, 2, 3 changes) remembered from the first memory task, $F(3, 27) = 1.09$, $p = .37$; $h_p^2 = .11$.

Discussion

As in Experiment 7, there was no interference between two concurrently performed VWM tasks, despite both tasks requiring

memory for color values. Together, Experiments 7 and 8 indicate that VWM can retain color information in parallel within two separate, specialized memory mechanisms.

There are three alternative explanations that might account for this pattern of dual-task independence between working memory tasks. First, despite performing an articulatory suppression task throughout each trial, participants might nonetheless have retained information about a subset of the colors using verbal working memory. Second, the dual-task independence might be explained by the use of separate, specialized memory systems for representing sequentially and simultaneously presented information rather than separate, specialized systems for representing object-based properties and snapshot-based features. Third, the dual-task independence might be explained by the use of separate, specialized memory systems for representing dynamic and static information rather than separate, specialized systems for representing object-based properties and snapshot-based features. However, the experiments presented in Wood (2009) rule out all three of these alternatives. Participants were tested with the same dual-task paradigm. Results showed that (1) verbal working memory does not retain a significant portion of information in this dual-task method; (2) observers do not use separate, specialized memory systems for retaining sequentially and simultaneously presented information in this dual-task method, and (3) observers do not use separate, specialized memory systems for retaining dynamic and static information in this dual-task method.⁶ Further, there is evidence that this dual-task method can produce significant interference between two VWM tasks: specifically, when both tasks require memory for (1) spatiotemporal information (see Experiment 3), (2) object identity information (Wood, 2009), or (3) view-dependent feature information (Wood, under review). All of these findings are predicted by the core knowledge architecture, but are not predicted by the spatial-object architecture or by other proposed architectures (see General Discussion).

There are two reasons to suspect that the color changes from the first memory task were retained in an object-based system while the color features from the second memory task were retained in a snapshot-based system. First, the storage capacity for the first memory task was approximately two feature's worth of information, which matches the storage capacities observed in previous studies that examined VWM for individually moving objects and object identities. Specifically, Wood (2009) showed that observers can retain information about the identities of approximately two 3D objects at once; Saiki (2003) reported a capacity estimate of approximately two objects in a paradigm in which objects moved periodically behind occluders; and Rasmussen and Hollingworth (2008) showed that observers can update memory for the colors of approximately two moving objects. In contrast to these two-item object-based limits, other studies show that observers can retain 3–4 colors when the features are presented in a scene (e.g., Luck & Vogel, 1997; Wood, 2009). Similarly, in the second memory task in the current experiment, participants could retain 3–4 colors when the features were presented in a scene. This suggests that participants remembered the colors from the second memory task using a snapshot-based VWM system.

Second, a previous study, which used this same dual-task method, showed that when observers try to remember 3D objects in the first memory task (rather than color changes) there is little to no interference between the two memory tasks (Wood, 2009).

Observers could retain approximately two 3D objects irrespective of the number of colored objects that they also retained from the second memory task, and they could retain 3–4 colored objects from the second memory task irrespective of the number of 3D objects that they also retained from the first memory task. As in Experiments 7–8, the items in the first memory task and the items in the second memory task did not compete with one another for the limited storage resources of a single working memory buffer.

Further research is needed, however, to characterize more precisely the conditions under which visual features are retained as properties of individual objects versus as features in a visual snapshot. Further research is also needed to show that the color features retained from the second memory task were, in fact, stored in a view-dependent format. Intriguingly, Jiang and colleagues (2000) have shown that in some contexts, VWM stores color features in relation to one another as parts of a larger spatial configuration; this binding of features to a larger spatial configuration corresponds to how features are stored in a view-dependent snapshot because a view-dependent snapshot contains the set of sensory readings obtained at a particular location in the environment (Trullier et al., 1997). Thus, the relational encoding of features in VWM provides evidence that a subset of color features in an array can be retained as a view-dependent snapshot.

General Discussion

Decades of research on adults, infants, and nonhuman animals provide evidence for three core knowledge systems that retain spatiotemporal information, object property/kind information, and view-dependent snapshots. Similarly, the current experiments, combined with the other studies described in this paper, provide evidence that VWM can be divided into separate, specialized systems that retain spatiotemporal information, object property/kind information, and view-dependent snapshot information. Thus, VWM contains a collection of separate, specialized mechanisms that parallel core knowledge systems. This core knowledge architecture of VWM links the study of the temporary storage of visual information to the study of the biological foundations of visual cognition.

These results place constraints on accounts of the processes that guide visual representation in humans. Specifically, they suggest that VWM contains three separate mechanisms that are specialized for retaining spatiotemporal information, object property/kind information, and view-dependent snapshot information. Thus, visual representation is constrained by three independent VWM storage limits: (1) a 2–3 item spatiotemporal-based limit (see also Wood, 2007; 2008), (2) a 2-item object-based limit (see also Rasmussen

⁶ To provide an additional test of this possibility, I conducted two supplementary experiments that further explored the conditions in which observers can retain color information in parallel for two VWM tasks. In the experiments (1) the same color values were used in both memory tasks, (2) the set sizes were reduced to 0–2 colors in the first memory task and 0–4 colors in the second memory task, and (3) the colors in both memory tasks were presented simultaneously at different predictable locations. Results revealed the same pattern of dual-task independence observed in Experiments 7–8, and this same pattern also obtained when the colors in both memory tasks were presented as dynamic color changes.

& Hollingworth, 2008; Saiki, 2003; Wood, 2009), and (3) a 3–4 item snapshot-based limit (see also Wood, 2009).

The core knowledge architecture proposes that the units of VWM are spatiotemporal representations, object property/kind representations, and view-dependent snapshot representations. Contrary to models that argue that VWM is best understood in terms of the number of objects or features that need to be remembered, this architecture therefore makes the counterintuitive prediction that in some cases it should be possible to store feature values from the same feature dimension in parallel within two VWM buffers. For example, given that color information can be part of a representation of an individual object and part of a representation of a view-dependent snapshot, it should be possible to retain color features in the object-based and snapshot-based memory mechanisms concurrently, with little to no interference between the two types of color information. This prediction was confirmed by Experiments 7–8.

Although this finding may seem counterintuitive, it converges with neuroimaging studies of the cortical substrates of VWM. These studies show that VWM retains information in multiple regions of the visual system, including early visual areas (V1–V4) and higher-order prefrontal, parietal, inferotemporal and lateral occipital areas (Harrison & Tong, 2009; Serences et al., 2009; Vogel & Machizawa, 2004; Xu & Chun, 2006). Representations in early visual areas are pixel-like pictorial representations of the scene, akin to snapshots. VWM representations retained within these early visual areas may therefore be view-dependent and could support visual processes that use snapshot information. In contrast, higher-order areas support object recognition mechanisms that represent perceived 3D shape, but not low-level image features (Kourtzi & Kanwisher, 2001). VWM representations retained within these higher-order areas may therefore be object-based and could support visual processes that operate over representations of individual objects. Critically, if VWM capacity is determined by local and independent neural circuits, then there should be at least two independent capacity limits on VWM, one reflecting the competition of snapshot-like information retained in early visual areas and one reflecting the competition of object identity-like information retained in higher-order areas.

Can These Findings be Explained by Existing Architectures of VWM?

This pattern of findings, in which VWM is subject to independent spatiotemporal-based, object-based, and snapshot-based storage limits, cannot be explained by existing models of the architecture of VWM. No proposed VWM architecture makes the critical distinction between object-based and snapshot-based *feature* representation. This distinction is necessary for two reasons: first, to account for the pattern of dual-task performance described here and elsewhere (Wood, 2009), and second, to explain how VWM supports the two core knowledge systems that retain object property/kind information and view-dependent snapshot information. Similarly, no proposed architecture makes the critical distinction between spatiotemporal-based and snapshot-based *spatial* representation. This distinction is necessary to account for existing dual-task findings (Wood, 2007; Zimmer et al., 2003) and to explain

how VWM supports the two core knowledge systems which retain spatiotemporal information and view-dependent snapshot information. Below I consider three of the most prominent models in the literature in more detail.

First, these dual-task findings cannot be explained by a VWM architecture that contains separate, specialized systems for spatial and object representation because observers can perform two spatial memory tasks or two object memory tasks concurrently with little to no competition between the tasks for the limited resources of a single VWM system. Specifically, when observers perform two working memory tasks that require memory for spatiotemporally defined movements and memory for the locations of dots in a scene, there is little to no competition between the two tasks for the limited storage resources of a single working memory system (Wood, 2007), despite both tasks requiring memory for spatial information. A VWM architecture that contains a single buffer for spatial information cannot account for this finding. Similarly, when observers perform two working memory tasks that require memory for individual objects and memory for features in a scene, there is little to no competition between the two tasks for the limited storage resources of a single VWM system (see also Wood, 2009), despite both tasks requiring memory for nonspatial feature information such as color and shape. As shown in Experiments 7–8, this independence between memory tasks occurs even when the object-based and snapshot-based tasks both requiring retaining information from the same feature dimension of color. A VWM architecture with a single buffer for object information cannot account for this finding. Thus, the spatial-object architecture does not make the critical distinction between object-based information used to represent individual objects and snapshot-based information used for view-dependent place recognition, nor does the spatial-object architecture make the critical distinction between spatiotemporal-based information used to track objects and snapshot-based information used to represent the locations of features in a view-dependent snapshot.

Second, these dual-task findings cannot be explained by a VWM architecture that regards all VWM representations as activated representations in long-term memory because this architecture predicts that the storage capacity of VWM will have a single limit, stemming from the number of representations that can be activated concurrently through attentional processes (Cowan, 2001). Contrary to this prediction, the present results, and those from previous studies (Wood, 2007, 2008, 2009), demonstrate that VWM is subject to independent storage limits for spatiotemporal information, object property/kind information, and view-dependent snapshot information. Importantly, however, a more general, central capacity limitation may limit visual memory in some contexts. An interesting direction for future research would be to examine the conditions under which the three VWM mechanisms described here do, and do not, interact with more central components of working memory.

Third, these dual-task findings cannot be explained by the VWM architecture proposed by Xu and Chun (2009), which contains two main components, object individuation and object identification. However, these architectures share a number of characteristics. First, they both propose dedicated components for object selection and object feature representation. For object

selection, Xu and Chun (2009) focused on the individuation of objects based on spatial information, whereas I have focused on the tracking of objects and the retention of spatiotemporal information in VWM. Nevertheless, for both architectures there are representations of objects that contain primarily spatiotemporal information. Similarly, for object feature representation, both the core knowledge architecture and Xu and Chun's (2009) architecture propose a specialized memory system for object identification/recognition. These architectures differ with regard to whether there is a third VWM component for retaining view-dependent snapshot information. Xu and Chun's theory does not make the distinction between object-based and snapshot-based representation, whereas the core knowledge architecture proposes separate memory components for retaining object property/kind information and view-dependent snapshot information.

Predictions of the Core Knowledge Architecture

The core knowledge architecture proposes that VWM contains three memory mechanisms that parallel core knowledge systems. This architecture makes a number of empirical predictions because core knowledge systems are both domain-specific (each system functions to represent a particular kind of entity) and task-specific (each system uses its representations to address specific questions about the world). Thus, each of these three VWM mechanisms should have a unique set of information processing "signatures" that reflect the fact that the mechanisms support domain-specific and task-specific cognitive processes.

Consider, for example, the case of the spatiotemporal-based VWM system, which is proposed to be related to the core knowledge system for object tracking. Coordinated studies of adults, infants, and nonhuman animals provide evidence for several information-processing signatures of object tracking. One signature is that object tracking privileges spatiotemporal information over surface feature information. A second signature is that object tracking depends on an allocentric reference frame rather than a retinotopic reference frame (Kellman, Spelke, & Short, 1986; Liu et al., 2005). If the object tracking system corresponds to the spatiotemporal-based VWM system, then both should show the same information-processing signatures. Thus far, studies have confirmed this prediction: there is evidence for a specialized working memory system that privileges spatiotemporal information over surface feature information (Wood, 2007, 2008) and retains information about the paths of tracked objects using an allocentric reference frame (Wood, 2010). Future studies could continue to investigate whether additional signatures of the object tracking system characterize the spatiotemporal-based VWM system.

Similarly, decades of experiments on adults, infants, and nonhuman animals have revealed many information-processing signatures of object recognition and place recognition. For example, researchers have characterized the main types of visual features used in object recognition and place recognition. Place recognition stores and matches view-dependent snapshots, which are sets of sensory readings obtained at particular locations in the environment (Gilner, 2008; Trullier et al., 1997). View-dependent snapshots therefore contain *metric*

properties, such as line lengths, angles of intersections, and degrees of curvature. In contrast, object recognition appears to be relatively insensitive to metric properties. Rather, object recognition is particularly sensitive to *nonaccidental properties*, properties of objects that are relatively unaffected by rotation in depth (e.g., Biederman, 1987; Biederman & Barr, 1999). Thus, according to the core knowledge architecture, the object property/kind memory system should primarily retain nonaccidental properties, whereas the place recognition memory system should retain metric properties. Studies of object recognition provide suggestive evidence for this prediction. Experiments using a sequential comparison procedure (a method that requires storing information in VWM) provide evidence for distinct memory mechanisms for retaining nonaccidental properties and metric properties (e.g., Biederman & Barr, 1999; Biederman & Cooper, 1992).

In addition to being domain-specific, core knowledge systems are also task-specific. Thus, the core knowledge architecture predicts that these three VWM components will interact in unique ways with other cognitive operations. For example, the spatiotemporal-based VWM system should primarily interfere with a concurrently performed object tracking task; the object property/kind VWM system should primarily interfere with a concurrently performed object recognition task; and the snapshot-based VWM system should primarily interfere with a concurrently performed place recognition task.

Future Directions

The core knowledge architecture proposes that VWM contains separate memory systems for spatiotemporal information, object property/kind information, and view-dependent snapshot information. For each of these VWM systems, one might ask a number of more specific questions. For example, on the mechanistic and functional levels:

1. What is the nature of the representations retained in each system: Are the units fixed, discrete representations (Zhang & Luck, 2008) or are storage resources distributed among all items (Bays & Husain, 2008)?
2. How does each system retain visual information: Are features from different feature dimensions retained as integrated representations (Luck & Vogel, 1997) or in parallel, feature-specific stores (Wheeler & Treisman, 2002)?
3. Which neural substrates support each system?
4. How do these systems interact with one another and with other visual processes (e.g., spatial attention and more general components of working memory)?
5. What particular functions does each VWM system support?

On the phylogenetic level, one might examine the distribution of these memory systems across species. This could illuminate the particular evolutionary pressures that led to the emergence of these different VWM systems. For example, most freely moving animals

navigate visually, whereas only animals that manipulate objects with hands (or beaks, fins, trunks, or tentacles) require 3D object representation. Thus, the view-dependent snapshot system and its associated snapshot-based memory mechanism may have evolved long before 3D object representation and its associated object-based memory system. On the developmental level, one might examine how these memory systems develop in the individual.

Finally, what is the relation of these VWM systems to other core knowledge systems? In addition to the object tracking, object recognition, and place recognition systems described here, there is also strong evidence for other core knowledge systems: (1) a number representation system that computes the approximate number of items in a set (reviewed by Feigenson, Dehaene, & Spelke, 2004), (2) an agent comprehension system for perceiving and understanding the behavior of other agents (e.g., Gergely, Bekkering, & Kiraly, 2002; Wood & Hauser, 2008; Woodward, 1998); (3) a reorientation system that uses the geometry of the 3D surface layout (Cheng, 1986; Gouteux et al., 2001; Hermer & Spelke, 1994; Lee & Spelke, 2010; Sovrano et al., 2003; Vallortigara et al., 1990; Wystrach & Beugnon, 2009), and (4) a social grouping system that identifies and reasons about potential social partners and social group members (Spelke & Kinzler, 2007). Do these core knowledge systems depend on the three VWM systems described here or do they depend on other, more specialized working memory systems? Variants of the dual-task method used here and elsewhere might prove especially useful in this exploration.

Conclusions

How do humans retain information about the visual environment? Many researchers argue that we rely on a VWM architecture with specialized components for spatial and object representation. However, studies of the biological foundations of visual cognition suggest a different view. Coordinated studies of adults, infants, and nonhuman animals provide evidence that visual cognition builds on a set of evolutionarily ancient systems that retain spatiotemporal information, object property/kind information, and view-dependent snapshots. Similarly, the current findings, combined with those from previous studies (e.g., Wood, 2007, 2008, 2009), provide evidence that VWM contains separate, specialized buffers that retain spatiotemporal information, object property/kind information, and view-dependent snapshot information. Thus, the architecture of VWM accords to a surprising degree with the innate architecture of the mind, as revealed through studies of infants and animals. VWM contains a collection of components that parallel core knowledge systems. This core knowledge architecture links the study of VWM to the study of the biological foundations of visual cognition.

This link could be fruitful in many ways. For the study of visual cognition, these findings link specific VWM components to the innate mechanisms that structure visual experience from birth. This could illuminate the origins of the various components of VWM, on both developmental and evolutionary timescales. For the study of the developmental psychology, these findings show how core knowledge systems correspond to the working memory mechanisms that support and limit mature visual thought.

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**Call for Papers: Special Section on Theory and Data in Categorization:
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