Journal of Experimental Psychology: General
2007, Vol. 136, No. 4, 639–652

0096-3445/07/$12.00 DOI: 10.1037/0096-3445.136.4.639

Visual Working Memory for Observed Actions

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Human society depends on the ability to remember the actions of other individuals, which is information that must be stored in a temporary buffer to guide behavior after actions have been observed. To date, however, the storage capacity, contents, and architecture of working memory for observed actions are unknown. In this article, the author shows that it is possible to retain information about only 2–3 actions in visual working memory at once. However, it is also possible to retain 9 properties distributed across 3 actions almost as well as 3 properties distributed across 3 actions, showing that working memory stores integrated action representations rather than individual properties. Finally, the author shows that working memory for observed actions is independent from working memory for object and spatial information. These results provide evidence for a previously undocumented system in working memory for storing information about actions. Further, this system operates by the same storage principles as visual working memory for object information. Thus, working memory consists of a series of distinct yet computationally similar mechanisms for retaining different types of visual information.

Keywords: visual working memory, working memory, actions, events

Human society depends on the ability to remember actions performed by other individuals, allowing for social interactions ranging from social learning to interpreting and explaining the behavior of others. To guide behavior, observed actions must be stored in a temporary buffer, known as *working memory*, to sustain information once the actions have been observed. To date, however, the working memory mechanisms that support the storage of information about observed actions are unknown. The present study investigated the nature of working memory for actions by characterizing its storage capacity, contents, and architecture.

Working Memory for Object Information

Over the past 2 decades, working memory for object information has been well studied. Specifically, objects are stored in visual working memory, the component of working memory that sustains visual information for up to several seconds (Logie, 1995). This working memory system operates by at least two principles. First, it has severe capacity limitations—it is possible to retain up to only three or four object representations at once (Alvarez & Cavanagh, 2004; Cowan, 2001; Jiang, Olson, & Chun, 2000; Luck & Vogel, 1997; Pashler, 1988). Second, the units of visual working memory are integrated object representations rather than individual properties. It is possible to retain 16 properties distributed across four objects as well as 4 properties distributed across four objects (Luck & Vogel, 1997).

Although objects are a basic unit of our visual experience, we do not experience the world statically. Rather, objects in our environment move and change, creating distinct perceptual events. When observing human behavior, for example, we experience the movement of body parts through time and parse those movements into discrete action units (see Zacks & Tversky, 2001). Thus, a mechanism is needed for storing information about agents and objects at different points in time so that we can process information about events after they have been observed. Nevertheless, the mechanisms allowing event information to be retained in working memory remain mostly unknown.[1]

Neural Substrates of Action and Object Processing

Neuroimaging studies show that distinct neural substrates support representations of objects and actions. For example, viewing images of the human body activates the lateral occipitotemporal area (Downing, Jiang, Shuman, & Kanwisher, 2001; Peelen, Wiggett, & Downing, 2006), whereas viewing bodily movements activates mirror neuron areas in the prefrontal cortex, an area that is insensitive to the identity of the acting agent (Ruby & Decety,

This work was supported by grants from the National Institute of Health (MH075298) and from Harvard University. I thank Jonathan Beier, Serena Butcher, Susan Carey, and Elizabeth Spelke for helpful comments on a draft of this article. Further, I thank Steve Lindsay, Steven Luck, and Geoff Woodman for helpful comments.

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[1] Previous studies have explored how the visual system updates information about an object's properties as the object moves over time (e.g., Kahneman, Treisman, & Gibbs, 1992). For instance, an *object-file* is a midlevel visual representation that tracks objects over time on the basis of spatial information and updates information about the object's properties. To be clear, the present study is not concerned specifically with the mechanisms that allow property information to be updated over time. Rather, it concerns the mechanisms that allow us to remember how agents and objects move and change over time. Similarly, when I refer to representations of observed actions and events, I reference representations of visual information, without regard to broader computations linking perception and action. Hommel and colleagues (see Hommel, 2004), for example, have proposed that the brain creates a transient network of bindings that temporarily link information between a perceptual event, an accompanying action, and the task context, which they have termed *event-files.* Of course, the representations of observed actions studied here may enter into broader perception–action distributive systems, analogous to object representations stored in working memory.

2001). Similarly, a transcranial magnetic stimulation study has provided causative evidence for this dissociation, showing that interference with the lateral occipitotemporal area impairs the discrimination of bodily identity, whereas interference with the prefrontal cortex impairs the discrimination of bodily actions (Urgesi, Candidi, Ionta, & Aglioti, 2006). Thus, the brain recruits separate neural substrates for processing information about object properties and actions.

Further, reasoning about objects and actions involves distinct types of processes (see Wynn, 1996). First, with a display of objects, the observer has perceptual access to the entire array at the same time, whereas with a sequence of actions the observer only has access to one element at a time. Second, we perceive distinct objects from spatially separated surfaces in the visual layout; in relative contrast, individuating actions is a complex task because each action consists of a structured series of motions. Third, objects have an enduring existence and exist at distinct points in space; actions, however, endure temporarily and may or may not occur in the same point in space. Fourth, we reason about objects by using a set of specialized principles, expecting objects to move as cohesive, bounded, solid units (Spelke, 1990), and we do not reason about observed actions by using these same principles. The fact that reasoning about objects and actions involves distinct principles and is supported by separate neural substrates raises an important question: Does the brain store information about separately processed object and action information in the same general working memory system or in distinct, specialized working memory systems?

Working Memory for Action Information

Two sets of studies provide some insight into how observed actions are retained in working memory. First, Smyth and colleagues (Smyth, Pearson, & Pendleton, 1989; Smyth & Pendleton, 1988) found that memory for spatial locations and memory for hand actions are distinct. In one experiment, participants were asked to reproduce a hand configuration span while performing either a spatial suppression task or a movement suppression task. They found that the movement suppression task, but not the spatial suppression task, interfered with memory for hand configurations. In a second experiment, participants were asked to perform a spatial memory task (Corsi block task), again while performing either the spatial or movement suppression task. In contrast to the first experiment, there was interference for the spatial suppression task but not for the movement task. This double dissociation between memory for spatial locations and hand movements provides evidence for distinct working memory systems for retaining information about spatial information and actions. Second, Rumiati and Tessari (2002) found that memory for meaningful and meaningless actions was significantly impaired when subjects performed a motor suppression task but not when they performed a verbal suppression task or a spatial suppression task. This indicates that memory for actions is not supported by the spatial or verbal components of working memory. Nevertheless, these studies do not address the storage capacity of working memory for action information, the nature of the action representations stored in working memory, or whether action information is stored separately from object information.

Overview of the Experiments

The present study had two goals. Initially, I wanted to characterize the storage capacity and contents of working memory for observed actions, focusing on three questions. First, what is the storage capacity of working memory for observed actions (Experiment 1–2)? Second, is the storage capacity of working memory different for different action properties (Experiment 3)? Third, what are the action units retained in working memory: Are they stored as individual properties or as integrated representations (Experiment 4)?

The second goal of the study was to investigate the nature of working memory for visual information more generally. Working memory is thought to be divided into two major components. The first component is a central executive system, which is hypothesized to be a central processor that is able to temporarily store and process information from multiple modalities. The second component consists of peripheral slaves systems, which temporarily store information from a single modality. One of these systems is the articulatory loop, which retains verbal information. The second major slave system is the visuospatial sketchpad, which is involved in the temporary maintenance of visual–spatial information (Baddeley, 1986). The visuospatial sketchpad is thought to be further divided into separate components for retaining visual information and spatial information (Logie, 1995). Thus, a general assumption is that the visual component retains information about a wide range of visual information, ranging from object properties to visual events. Experiments 5–6 test this assumption by asking whether working memory stores information about actions and objects in a general visual memory store or in separate, specialized visual memory stores. Experiment 7 tests whether memory for observed actions is distinct from spatial working memory in the present testing context.

Experiment 1

Experiment 1 investigated the storage capacity of working memory for observed actions. I developed a variant of the sequential comparison procedure (Phillips, 1974) used previously to measure the storage capacity of visual working memory for object information (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). On each trial, participants viewed a sample sequence of actions, consisting of one to five actions performed by a computer-generated human figure, and a test sequence of actions, separated by a brief delay, and then indicated whether the two sequences were identical or different in terms of one of the actions (see Figure 1). Participants' accuracy was computed as a function of the number of actions in the stimulus sequence (the set size) to determine the number of observed actions that can be accurately retained in working memory at one time. To demonstrate that any resulting estimate of storage capacity accurately reflects limitations in visual working memory with no significant contribution from verbal memory, participants performed a concurrent articulatory suppression task that inhibits the use of verbal coding in the memory task (Baddeley, 1986; Besner, Davies, & Daniels, 1981; Woodman, Vogel, & Luck, 2001).

It was also necessary to demonstrate that any impaired performance for larger set sizes did not occur because participants were required to retain larger numbers of actions for a greater amount of

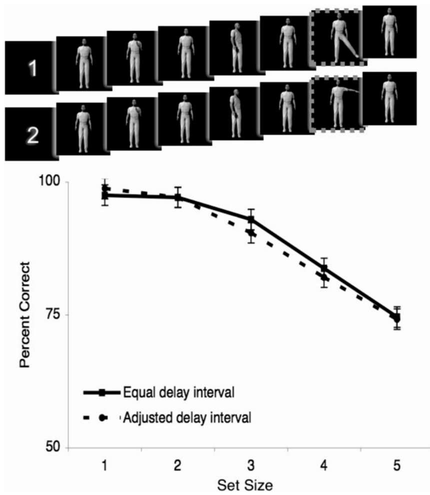

Figure 1. Example of action sequences and performance on the sequential comparison procedure for Experiment 1. Schematic illustration of a sample sequence (top panel) and test sequence (bottom panel) consisting of three actions. This example depicts a change from sample to test in the final action of the sequence. In the equal delay interval condition, the sample and test sequences were separated by a 1,500-ms delay for all set sizes. In the adjusted delay interval condition, the delay interval was varied so that participants retained information about each observed action for the same amount of time for all set sizes. Error bars represent 95% confidence intervals for within-subject designs as described by Masson and Loftus (2003).

time. To address this possibility, participants were tested in a second condition in which the duration of the delay interval between the sample sequence and test sequence was adjusted accordingly for Set Sizes 1–4 so that information about each action needed to be retained for an equal amount of time across all set sizes.

Method

Participants. Ten participants (male: 4; female: 6) between the ages of 16 and 30 with normal or corrected-to-normal vision participated to receive credit toward a course requirement or for monetary payment. These age and vision characteristics applied to the participants tested in all experiments reported in this study. Informed consent was obtained.

Stimuli. The action sequences consisted of one to five actions performed by a computer-generated figure subtending 10.5° (height) × 4° (width) in the center of a video monitor with a black background. Each action lasted 500 ms and was preceded by 500 ms of no motion. During the 500-ms pause between actions, the figure was in a neutral position (see Figure 1). The type of action was selected at random from a set of seven highly discriminable actions: forearm curl, arm raise, head turn, body turn, hand grasp, knee raise, and leg raise. To be clear, when I refer to "an action," I reference these actions in their entirety as opposed to the sub-acts that compose them. After performing an action, the figure returned back to a neutral position before performing the next action (see Figure 1). The same action could be presented more than once in each sequence. The figure performed each action on the left side of his body.

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. The offset of these letters was followed by a 1,000-ms presentation of a screen displaying the number *1* (to designate the sample sequence), followed by the presentation of the sample sequence of actions. The sample sequence was followed, after a 500-ms delay interval, by a 1,000-ms presentation of the number *2* (to designate the test sequence), followed by the presentation of the test sequence of actions. The test sequence was identical to the sample sequence, except that on 50% of the trials one of the actions was changed to a new randomly selected action type. Thus, the actions were presented in the same order in the sample sequence and the test sequence. The position of the changed action occurred equally often in each serial position of the sequence. Participants were required to make a response to the test array, indicating whether the sample sequence and the test sequence were identical or differed in terms of one of the actions. The changed action could have occurred in some other serial position in the trial; thus, to succeed, participants needed to remember which action occurred in each serial position. Across all set sizes, accuracy was nearly identical when the changed action did and did not occur in some other serial position.

In the adjusted delay interval condition, the delay intervals were adjusted so that participants were required to retain information about each observed action for the same amount of time for all set sizes. The delay intervals were 5,500 ms (one action); 4,500 ms (two actions); 3,500 ms (three actions); 2,500 ms (four actions); and 1,500 ms (five actions).

The equal delay interval condition and the adjusted delay interval condition were tested in separate blocks, each of which contained 24 trials at each set size. The order of condition was randomized across participants. Before each block, participants received 20 practice trials.

Participants' data were excluded from the final analysis if their total performance across all set sizes and conditions differed by more than two standard deviations from the group. This criterion resulted in no more than 1 participant being excluded from any experiment.

Results and Discussion

Participants' accuracy was analyzed with an analysis of variance (ANOVA), with variables of set size and condition (equal delay interval vs. adjusted delay interval).[2] This analysis yielded a highly significant main effect of set size, $F(4, 9) = 72.49$, $p < .001$, $h_p^2 = .89$. The main effect of condition, $F(1, 9) < .34$, $p = .58$, $h_p^2 = .04$, and the interaction, $F(4, 9) = .72$, $p = .58$; $h_p^2 = .07$, did not approach significance (see Figure 1). This shows that performance was not significantly influenced by variations in the delay intervals. Thus, the errors at Set Sizes 3–5 reflect limitations in storage capacity rather than limitations in memory maintenance.

[2] Errors in this task can be characterized as misses (responding *same* on trials in which an action changed), or false alarms (responding *different* on trials in which all actions remained the same). In all the experiments reported here on memory for action information, misses were approximately 1.7 times as common as false alarms.

Performance was almost perfect for sequences containing one and two actions and then declined systematically as the set size increased from three to five actions (see Figure 1). To provide a more quantitative measure of storage capacity, I used the formula that was developed by Pashler (1988) and improved on by Cowan (2001). The logic of this approach is that if an observer remembers k actions from a sequence consisting of n actions, then the observer should be able to detect a change in one of the actions on k/n trials. This approach 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 $k = n \times (H - F)$. For all conditions, k was calculated and averaged for set sizes containing four and five actions. Through the use of this approach, these data show that participants were able to retain 2.58 actions in working memory at one time in the equal delay interval condition and 2.49 actions in the adjusted delay interval condition. Further, this experiment shows that working memory representations of bodily actions are relatively robust and can be maintained in memory for at least up to 5.5 s, with minimal decay of information.

These results are consistent with studies showing that observers can remember a limited number of actions at one time (Rumiati & Tessari, 2002; Smyth et al., 1989; Smyth & Pendleton, 1988). Furthermore, this two- to three-item estimate accords with previous studies showing that observers can retain between three and four objects in visual working memory (Luck & Vogel, 1997). Thus, visual working memory has common storage limits for retaining information about objects and actions. Next, I investigated the nature of the action representations stored in working memory.

Experiment 2

In Experiment 2, I asked whether the storage capacity of working memory is determined by the number of observed actions or by the total amount of observed motion. The capacity of working memory for verbal information has been shown to depend on the phonological length of the words being retained, such that longer words require more memory capacity than do shorter words (Baddeley, Thomson, & Buchanan, 1975). Similarly, it is possible that participants can retain a finite amount of observed motion in working memory, independent of the number of actions. If observed actions are stored in a duration-dependent store, then participants should retain fewer actions when the sequences consist of longer actions. In one condition, participants viewed actions that persisted for longer durations with shorter delays between actions, and in a second condition, participants viewed actions that persisted for shorter durations with longer delays between actions.

Method

Ten new participants (male: 4; female: 6) participated in this experiment. The stimuli and procedure used in Experiment 2 were identical to those used in Experiment 1, except for the duration of the actions and inter-action intervals. In one condition, participants viewed actions that persisted for 500 ms with a 750-ms delay between actions, and in a second condition, participants viewed actions that persisted for 750 ms with a 500-ms delay between actions, thus creating action sequences with identical total durations but varying amounts of total motion. It should be noted that the two conditions were confounded in terms of the duration of the actions and the inter-action interval, which was necessary to avoid confounding the total duration of the action sequences. However, there is no reason to suspect that this might influence the results.

Results and Discussion

The ANOVA conducted with variables of set size (one to five actions) and condition (longer actions vs. shorter actions) yielded a highly significant main effect of set size, $F(4, 9) = 82.49$, $p < .001$, $h_p^2 = .90$. The main effect of condition, $F(1, 9) = .002$, $p = .97$, $h_p^2 = .00$, and the interaction, $F(4, 9) = .42$, $p = .79$, $h_p^2 = .05$ (see Figure 2), did not approach significance. Cowan's (2001) formula shows that participants were able to retain 2.25 of the 500-ms actions and 2.20 of the 750-ms actions at one time. Performance was nearly identical for both conditions, indicating that the storage capacity of working memory is determined by the number of actions rather than by the total duration of observed motion. That is, unlike the storage capacity of working memory for verbal information, which depends on the length of the items being retained, longer actions do not take up more storage space in working memory than do shorter actions. Of course, this conclusion may apply to shorter actions, such that longer actions that differ by a greater ratio of duration will require more working memory resources. Nevertheless, the total duration of motion in the action sequences differed by a 2:3 ratio, which should have resulted in a capacity reduction of approximately one action if the capacity of working memory for action information was determined exclusively by the amount of motion.

Experiments 3–4 further investigated the nature of the action representations stored in working memory. Experiment 3 asked whether the storage capacity of working memory is different for different action properties. Experiment 4 asked whether actions are

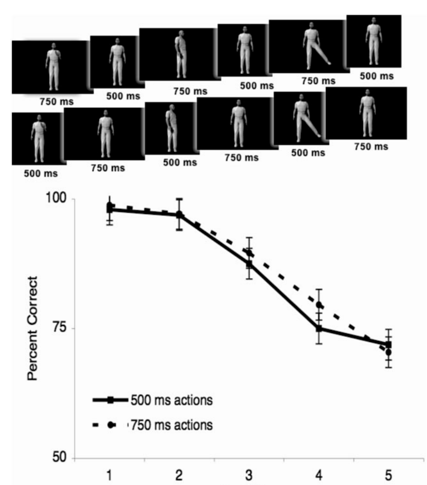

Figure 2. Schematic illustration of action sequences and performance (Experiment 2) for longer actions (750 ms) and shorter delays (500 ms; top panel) compared with shorter actions (500 ms) and longer delays (750 ms; bottom panel). The width of each frame depicts the duration of the event. Error bars represent 95% confidence intervals for within-subject designs as described by Masson and Loftus (2003).

stored in working memory as individual properties or as integrated actions.

Experiment 3

Experiment 3 investigated whether the storage capacity of working memory is different for different action properties (action type vs. action duration). In separate conditions, participants were presented with sequences containing from one to five actions and were asked to detect either a change in action type or a change in action duration.

Method

Ten new participants (male: 4; female: 6) participated in this experiment. Participants performed the same sequential comparison task used above, with sequences consisting of one to five actions that could vary in the type of action or in the duration of the action (500 ms and 1,000 ms). Because the range of motion was identical for both durations, the longer actions also contained slower motion speed. In one condition, only the type of action could change between the sample sequence and the test sequence, and participants were asked to report a change in action type. In the second condition, only duration could vary between the sample sequence and the test sequence, and participants were asked to report a change in duration. The order in which they were tested on each condition was counterbalanced across participants.

Results and Discussion

The ANOVA with variables of set size (one to five actions) and condition (action type vs. action duration) yielded a main effect of set size, $F(4, 9) = 122.40$, $p < .001$, $h_p^2 = .93$. The main effect of condition, $F(1, 9) = 2.10$, $p = .18$; $h_p^2 = .19$, and the interaction, $F(4, 9) = .54$, $p = .71$, $h_p^2 = .06$, did not approach significance. Cowan's (2001) formula shows that participants were able to retain similar numbers of actions defined by action type (2.35 actions) and action duration (2.70 actions; see Figure 3). Thus, working memory has similar storage capacities for different types of action properties.

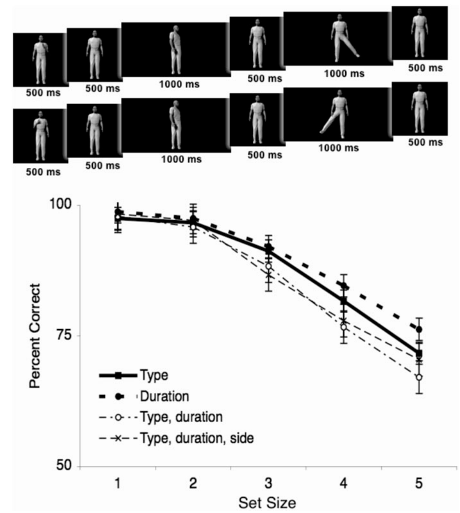

Figure 3. Schematic illustration of action sequences and performance (Experiments 3–4) when the actions could vary from the sample sequence to the test sequence by one property (action type or action duration), two properties (action type and action duration), or three properties (action type, action duration, and side of the body on which the action was performed). In the one- and two-property conditions, the figure performed all actions on his left side (top panel), and in the three-property condition the figure performed the actions on either his left or right side (bottom panel). Error bars represent 95% confidence intervals for within-subject designs as described by Masson and Loftus (2003).

Experiment 4

Experiment 4 investigated whether action properties are stored in working memory as integrated representations or as individual properties. This was tested by comparing memory for individual action properties (Experiment 3) with memory for actions defined by a conjunction of properties. If the units of working memory for actions are individual properties, then performance should decline more quickly with greater set sizes as participants are required to encode a greater number of properties for each action. In contrast, if the units of working memory are integrated action representations, then performance for a given number of actions should be similar regardless of whether participants are required to retain one property or multiple properties for each action.

Method

Ten new participants (male: 4; female: 6) participated in this experiment. Participants performed the same sequential comparison task used above, with sequences consisting of one to five actions that could vary in the type of the action, the duration of the action (500 ms and 1,000 ms), and the side of the body on which the action was performed (left or right). In one condition, either the type of action or the duration could vary from the sample sequence to the test sequence, and participants were asked to report a change in either of these properties. In the second condition, the actions could vary in action type, duration, or side, and participants were asked to report a change to any one of these three properties. Thus, for the conditions in Experiment 3, participants needed to remember three properties to obtain accurate performance with a set size of three actions, whereas for the conditions in Experiment 4, participants needed to remember six and nine properties to obtain accurate performance with a set size of three actions. The order in which participants were tested on each condition was counterbalanced across them.

Results and Discussion

Figure 3 depicts the data from Experiments 3 and 4. The ANOVA with variables of set size (one to five actions) and condition (two-property conjunction vs. three-property conjunction) yielded a significant main effect of set size, $F(4, 9) = 69.41$, $p < .001$, $h_p^2 = .89$. The main effect of condition, $F(1, 9) = .20$, $p = .67$, $h_p^2 = .02$, and the interaction, $F(4, 9) = .33$, $p = .86$, $h_p^2 = .04$, did not approach significance. However, there was a small decline in performance when participants were asked to remember actions that could differ by two and three properties (Experiment 4) compared with one property (Experiment 3), $F(1, 18) = 7.18$, $p = .02$, $h_p^2 = .29$. According to Cowan's (2001) equation, participants retained 1.92 actions when the actions were defined by a conjunction of two properties (action type, duration) and 2.14 actions when the actions were defined by a conjunction of three properties (action type, duration, side of the body). Across all set sizes, accuracy for detecting the changed action was nearly identical when the action changed in type versus duration (two-property conjunction) as well as in type versus duration versus side (three-property conjunction).

In summary, it is possible to retain nine properties distributed across three actions almost as well as three properties distributed across three actions. This indicates that working memory stores integrated action representations as opposed to individual properties. These results parallel with findings that observers can retain approximately three objects at one time (Luck & Vogel, 1997; Vogel & Machizawa, 2004; Vogel et al., 2001; Xu & Chun, 2005), independent of the number of simple features that must be encoded for each object (Luck & Vogel, 1997; Vogel et al., 2001). Thus, for both observed actions and objects, working memory (a) has a storage capacity of between three and four items and (b) stores those items as integrated representations, showing that working memory retains information about observed actions and objects using the same storage principles.

Participants retained about one fifth less of an observed action when they were required to remember a conjunction of properties. A recent study shows that working memory for objects is also slightly impaired for items consisting of a conjunction of features compared with items consisting of single features for sequential, but not simultaneous, presentations (Allen, Baddeley, & Hitch, 2006). Thus, for both objects and observed actions, there is a small impairment in visual working memory when retaining information about items defined by a conjunction of properties during sequential presentations. This adds further evidence that working memory operates by common principles for storing information about observed actions and objects.

One alternative explanation for the finding that the storage capacity of working memory is determined by the number of actions rather than by the number of properties that need to be encoded is that there are independent property-specific memory stores for retaining information about action type, action duration, and the side of the body on which the action was performed. If these hypothesized property stores have independent capacities, then the number of properties that can be retained should double or triple as the number of property dimensions increases but without these properties being bound into integrated representations (see Wheeler & Treisman, 2002, for an analogous argument with regard to object representation). One way to disprove this alternative is to show that participants can accurately detect the changed action in the test sequence when it consists of a combination of properties that were present in separate actions in the sample sequence (Wheeler & Treisman, 2002). Although Experiment 4 was not specifically designed to test this account, there were only two possible durations and two possible sides; thus, for a large subset of the trials, the changed action necessarily consisted of a combination of action properties that were present in separate actions in the sample sequence. Nevertheless, performance was nearly identical when participants needed to encode two properties and three properties for each action, and only slightly impaired when participants needed to encode a conjunction of properties compared with single properties in Experiment 3. This pattern suggests that working memory stores action information as integrated representations rather than in independent property-specific memory stores.

Is the storage capacity of working memory for action information best characterized by a capacity limit between two and three actions, or can larger numbers of actions be stored at a lower fidelity of representation? When viewing sequences consisting of five actions, for example, observers might maintain representations of all five actions, but less precisely compared with when they only need to encode three actions. To shed light on this question, I asked whether performance for detecting the changed action differed as a function of its position in the sequence (see Figure 4). If working memory can retain more than two or three actions but at a lower fidelity of representation, then performance for detecting the changed action should be similar for all positions in the sequence. However, if working memory has a storage capacity of only two or three actions, then performance should be higher for either the first three actions, if there is a primacy effect, or for the last three actions, if there is a recency effect. For all conditions in Experiments 1–4, when observing sequences consisting of five actions, performance was higher when the changed action occurred in the first (75%, SD = 29%), second (70%, SD = 22%), and third (78%, SD = 23%) position, compared with the fourth (59%, SD = 31%) and fifth (58%, SD = 37%) position, $F(1, 79) = 23.38$, $p < .001$, $h_p^2 = .29$. This same qualitative pattern was obtained for all conditions in the experiments. This pattern suggests that working memory stores the first three actions and fails to encode additional actions once the working memory mechanism is exceeded. However, it is also possible that working memory stores higher fidelity representations of the first three actions and lower fidelity representations of additional actions.

Experiment 5

In Experiment 5, I asked whether working memory stores action and object information in one general memory store or in distinct, specialized working memory stores that operate by the same storage principles. Participants were tested in a dual-task paradigm, comparing arrays of objects containing zero, two, four, or six objects while maintaining zero, one, two, or three observed actions in working memory (see Figure 5). The procedure was

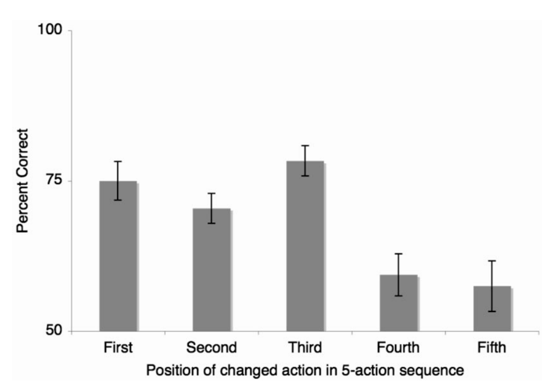

Figure 4. Accuracy in Experiments 1–4 for detecting the changed action, as a function of the position of the action in the five-action sequences. Error bars represent standard errors.

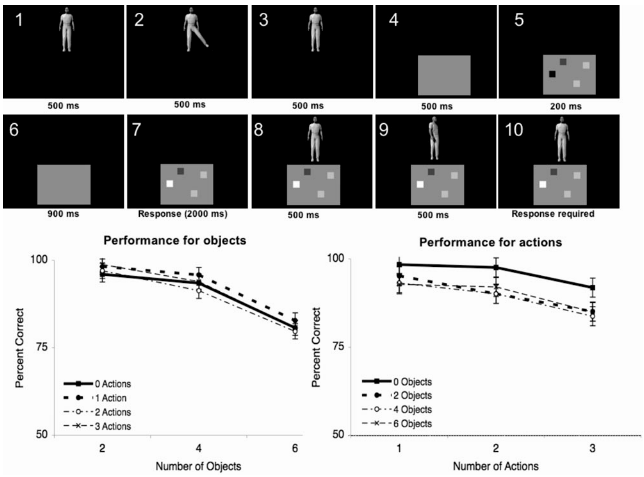

Figure 5. Example of stimuli and performance for Experiment 5. Participants viewed a sample sequence of actions (Frames 1–3), a sample array of objects (Frame 5), a test array of objects (Frame 7), and then a test sequence of actions (Frames 8–10). Participants indicated whether the sample and test arrays were identical or different in terms of one of the colors and whether the sample and test sequences were identical or different in terms of one of the actions. This example depicts an action change and an object change. Error bars represent 95% confidence intervals for within-subject designs as described by Masson and Loftus (2003).

identical to Experiment 1 except that in the delay interval between the sample sequence and the test sequence participants performed a comparison task between a sample array and test array of colored objects, indicating whether the two arrays were identical or differed in terms of the color of one of the objects (Luck & Vogel, 1997). Participants were therefore required to retain both the sample array (object information) and the sample sequence (action information) in memory at one time before responding to either the test array or the test sequence, all while performing the verbal suppression task. If working memory stores information about objects and observed actions in a general memory store, then memory for objects should be impaired when greater numbers of actions are maintained in memory, and memory for actions should decline as participants are required to compare greater numbers of objects. However, if working memory stores information about actions and objects in distinct memory stores, then memory for one type of visual information should be independent from memory for the other type of visual information.

Method

Ten new participants (male: 4; female: 6) participated in this experiment. Experiment 5 was identical to the above experiments except that participants performed a sequential comparison procedure with object information, comparing a sample array and a test array of objects, between the sample and test sequences. After viewing each sample sequence consisting of zero to three actions, participants viewed a briefly presented sample array of objects (200 ms) and a test array of objects (2,000 ms), separated by a brief delay (900 ms), and indicated whether the arrays were identical or differed in terms of the color of one of the objects. The action sequence was presented on the top half of the screen, and the object array was presented on the bottom half of the screen (see Figure 5). The arrays (13° × 9.5°) consisted of zero, two, four, or six colored squares (1.5° × 1.5°) presented on a gray background. In the trials presenting zero objects, only the gray background appeared. The color of one of the objects in the sample array was different from the corresponding object in the test array on 50% of the trials. When participants responded, they were then shown the test sequence of actions and indicated whether that sequence was the same or different from the sample sequence observed before the object comparison task. Before participating in the dual-task condition, participants completed the equal delay interval condition from Experiment 1 in order to familiarize themselves with the action stimuli.

To ensure that participants attended to both the action information and the object information, participants' data were excluded from the final analysis if their performance across all set sizes for the action trials or for the object trials was more the two standard deviations below the performance of the other participants.

Results and Discussion

Memory for objects. The ANOVA with variables of set size (two, four, six objects) and load (one, two, three actions) revealed a main effect of set size, $F(2, 9) = 67.36$, $p < .001$, $h_p^2 = .88$. The main effect of load, $F(2, 9) = 2.37$, $p = .12$, $h_p^2 = .21$, and the interaction, $F(4, 9) = .40$, $p = .81$, $h_p^2 = .04$, were not significant. The presence of a memory load of one, two, or three observed actions had no significant effect on the storage capacity of visual working memory for objects. Furthermore, an ANOVA with variables of set size (two, four, six objects) and presence of load (zero actions vs. one, two, three actions) yielded a main effect of set size only, $F(2, 9) = 156.57$, $p < .001$, $h_p^2 = .95$. The main effect of presence of load, $F(1, 9) = .18$, $p = .68$, $h_p^2 = .02$, and the interaction, $F(2, 9) = .20$, $p = .83$, $h_p^2 = .02$, did not approach significance.

Memory for actions. The ANOVA with variables of set size (one, two, three actions) and load (two, four, six objects) revealed a main effect of set size, $F(2, 9) = 11.84$, $p = .001$, $h_p^2 = .57$. The main effect of load, $F(2, 9) = .197$, $p = .82$, $h_p^2 = .02$, and the interaction, $F(4, 9) = .37$, $p = .83$, $h_p^2 = .04$, did not approach significance. However, an ANOVA with variables of set size (one, two, three actions) and presence of load (zero objects vs. two, four, six objects) revealed a significant main effect of set size, $F(2, 9) = 20.48$, $p < .001$, $h_p^2 = .70$, and presence of load, $F(1, 9) = 20.36$, $p = .001$, $h_p^2 = .69$. Thus, there was a significant decline in memory for actions in the dual-task condition (two, four, six objects) compared with the action memory alone condition, irrespective of whether there were two, four, or six objects in the comparison arrays. The fact that there was no change in memory for actions as a function of the number of objects maintained in memory shows that working memory for actions and working memory for objects are nearly independent. The small impairment in performance between the dual-task trials (two, four, six objects) and the action memory alone trials (zero objects) is consistent with studies showing that the storage capacity of visual working memory is a product of both local stage-specific operations and a central, executive process that impedes the simultaneous execution of distinct cognitive tasks under high demands (Baddeley, 1986; Baddeley, Chincotta, & Adlam, 2001; Fougnie & Marois, 2006;

Morey & Cowan, 2004; Ruthruff & Pashler, 2001) and may correspond to a supervisory attention system mediating goal and task setting (Norman & Shallice, 1986).

Experiment 5 shows that the storage capacity of working memory for action information is independent of the number of objects stored in memory and that the storage capacity of working memory for object information is independent of the number of actions stored in memory. Thus, working memory can be divided into separate systems for storing information about observed actions and objects.

An alternative explanation of the results of Experiment 5 is that the participants were able to increase the number of entities that they could remember by "chunking" those representations into sets on the basis of spatial location. Evidence in support of this proposal comes from studies showing that nonhuman primates, human infants, and human adults can increase the number of objects that can be stored in memory when those objects are grouped into distinct spatial locations or depth planes (Feigenson, Hauser, & Carey, 2002; Hauser, Carey, & Hauser, 2000; Xu & Nakayama, 2003). To test this alternative explanation, Experiment 6 presented the actions and objects in the same spatial location. If observers are able to increase their working memory capacity for actions and objects by chunking information on the basis of spatial information, then observers should only be able to remember a combination of up to three actions and objects. In contrast, if working memory consists of distinct visual memory stores for object and action information, then participants should still be able to retain two or three actions and three or four objects simultaneously, even when the entities are presented in the same spatial location.

Experiment 6

Experiment 6 was also designed to investigate the nature of the small decline in memory for actions in the dual-task condition compared with the action memory alone condition. The impairment could have resulted because participants were required to make two separate response decisions for each trial (one to the object test array and a second to the action test sequence) or because of executive processes that impede the simultaneous execution of distinct cognitive tasks under high demands (e.g., Baddeley, 1986). To distinguish between these possibilities, I used a partial report measure. After viewing the sample action sequence and object array, participants were presented with either a test action or a test object and indicated whether they had seen that action or object previously in the sequence. Participants therefore made only one response decision per trial.

Method

Ten new participants participated (male: 5; female: 5) in this experiment. Experiment 6 was identical to Experiment 5, except in the following ways. First, both the sample sequence of actions and the array of objects were presented in the middle of the screen. Second, no action or object was presented more than once in the sample sequence or sample array. Third, the object array was presented for 500 ms and consisted of two, four, or six colored squares (red, orange, yellow, green, blue, white, purple) on a black background. For the two-object arrays, the objects were presented on the horizontal midline, offset 3.5° from the center of the screen. For the four-object arrays, the objects were presented equidistant from the middle of the screen in four quadrants, offset 3.5° from the horizontal midline and 1.5° from the vertical midline. For the six-object arrays, two objects were presented on the horizontal midline, offset 3.5° from the middle of the screen, and the remaining four objects were offset 3° above and below those objects. Fourth, after viewing the sample action sequence and sample object array, the word *test* appeared (500 ms), followed by either a single action (50% of trials) or a single object (50% of trials), presented in the center of the screen. Participants were then asked to indicate whether that action or object was present in the sample action sequence or in the sample object array. When an action appeared in the test position, it was different from all of the actions in the sample sequence on 50% of the trials. Similarly, when an object appeared in the test position, it was different from all of the objects in the sample array on 50% of the trials. Fifth, participants received 24 trials for each set size combination of actions (zero, one, two, three) and objects (zero, two, four, six). Finally, participants did not complete the equal delay interval condition from Experiment 1 prior to this experiment. See Figure 6 for a schematic illustration of a trial.

Results and Discussion

Memory for objects. The ANOVA with variables of set size (two, four, six actions) and load (one, two, three actions) revealed a significant main effect of set size, $F(2, 9) = 25.34$, $p < .001$, $h_p^2 = .74$. The main effect of load, $F(2, 9) = .68$, $p = .52$, $h_p^2 = .07$, and the interaction, $F(4, 9) = .82$, $p = .52$, $h_p^2 = .08$, did not approach significance. Thus, working memory for objects is independent of the number of actions maintained in memory. Furthermore, an ANOVA with variables of set size (two, four, six objects) and presence of load (zero actions vs. one, two, three actions) revealed a main effect of set size only, $F(2, 9) = 40.91$, $p < .001$, $h_p^2 = .82$. The main effect of load, $F(1, 9) = .70$, $p = .43$, $h_p^2 =$

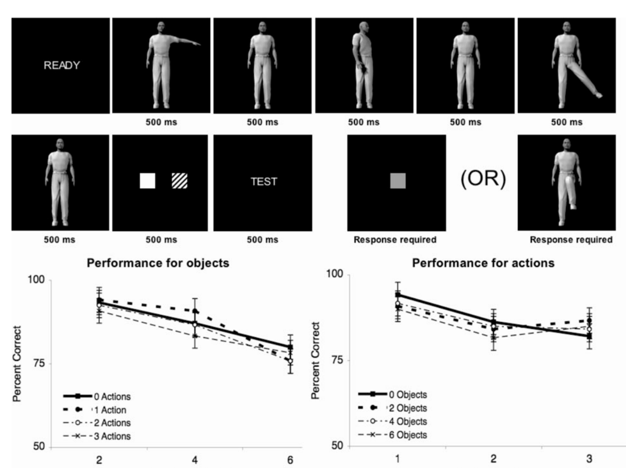

Figure 6. Schematic illustration of a trial and performance for Experiment 6 when the action sequence and object array appeared in the same location, and participants were required to make only one response decision per trial. This example depicts an object change and an action change. Error bars represent 95% confidence intervals for within-subject designs as described by Masson and Loftus (2003).

.07, and the interaction, $F(2, 9) = .82$, $p = .52$, $h_p^2 = .05$, did not approach significance.

Memory for actions. The ANOVA with variables of set size (one, two, three actions) and load (two, four, six objects) revealed a significant main effect of set size, $F(2, 9) = 5.60$, $p = .01$, $h_p^2 = .38$. The main effect of load, $F(2, 9) = .35$, $p = .71$, $h_p^2 = .04$, and the interaction, $F(4, 9) = .23$, $p = .92$, $h_p^2 = .03$, did not approach significance. Thus, working memory for actions is independent of the number of objects maintained in memory. Furthermore, an ANOVA with variables of set size (one, two, three actions) and presence of load (zero objects vs. two, four, and six objects) revealed a main effect of set size only, $F(2, 9) = 8.25$, $p = .003$, $h_p^2 = .48$. Unlike in Experiment 5, the effect of load was not significant, $F(1, 9) = .35$, $p = .57$, $h_p^2 = .04$. There was no impairment on memory for actions when participants were also required to remember objects. However, there was a nearly significant interaction between set size and load, $F(2, 9) = 3.47$, $p = .053$, $h_p^2 = .28$. Memory for actions was slightly better for set sizes with one and two actions, but not three actions, when there was an object load of two, four, or six objects. Thus, the small impairment in the dual-task condition in Experiment 5 most likely resulted predominantly because participants needed to make two response decisions per trial. However, the nearly significant interaction between set size and load suggests that executive processes independent of decision processes may also contribute to this effect.

This experiment replicates the pattern of results obtained in Experiment 5, providing further support for the claim that working memory for observed actions and objects are independent. This conclusion cannot be explained by appealing to mechanisms of spatial memory chunking because the actions and objects appeared in the same location.

Experiment 7

Experiment 7 tests whether working memory for actions is distinct from working memory for location information. As discussed in the introduction, studies have suggested previously that working memory for actions and spatial locations are distinct. There are, however, substantial methodological differences between those studies and the present one that made it necessary to test whether this dissociation also applies in the present context. For instance, Smyth and colleagues (1989; Smyth & Pendleton, 1988) asked participants to observe and then reproduce a series of hand movements. In contrast, in the present method participants compare the sample and test sequences on the basis of the visual properties of the actions. Additionally, Smyth and colleagues tested whether memory for actions and memory for locations recruit common processes by asking participants to perform one task (i.e., encode action information) while concurrently performing a secondary task (i.e., moving their hand between different spatial locations repeatedly). In contrast, the present method tests whether different types of visual information are retained in common or distinct memory stores by presenting the two types of information separately and then by measuring the degree to which varying memory loads for one type of information interferes with varying memory loads for the other type of information.

Participants were presented with zero to three actions followed by an array containing zero, two, four, or six dot locations. Then, at test, they were shown either a single action or a single dot location and indicated whether that action or location was present in the sample action sequence or dot array. Thus, participants needed to retain both the action information and the location information simultaneously. As in the previous experiments, participants also performed a verbal suppression task.

Method

Ten new participants (male: 5; female: 5) participated in this experiment. Experiment 7 was identical to Experiment 6, except instead of viewing an array with colored squares participants viewed a grid containing varying numbers of dot locations. After viewing the sample sequence of actions, a visible empty 5 × 5 grid (17.5° width × 14.5° height) was presented for 400 ms on a black background. Then, a memory array of zero, two, four, or six white dots (2° in diameter) was presented for 500 ms at randomly selected locations within the grid. After a 1,200-ms retention interval, participants then viewed either an action or a single dot within the grid and were asked to indicate whether that action or location was present in the sample sequence or the sample array (see Figure 7 for a schematic illustration of a trial). This spatial working memory task has produced consistent and reliable results in previous studies investigating visual working memory for spatial locations (Jiang, Olson, & Chun, 2000; Kumar & Jiang, 2005).

Results and Discussion

Memory for spatial locations. The ANOVA with variables of set size (two, four, six actions) and load (one, two, three locations) revealed a significant main effect of set size, $F(2, 9) = 4.91$, $p < .02$, $h_p^2 = .35$. The main effect of load, $F(2, 9) = .03$, $p = .98$, $h_p^2 = .00$, and the interaction, $F(4, 9) = .11$, $p = .98$, $h_p^2 = .01$, did not approach significance. Thus, working memory for spatial locations is independent of the number of actions maintained in memory. Furthermore, an ANOVA with variables of set size (two,

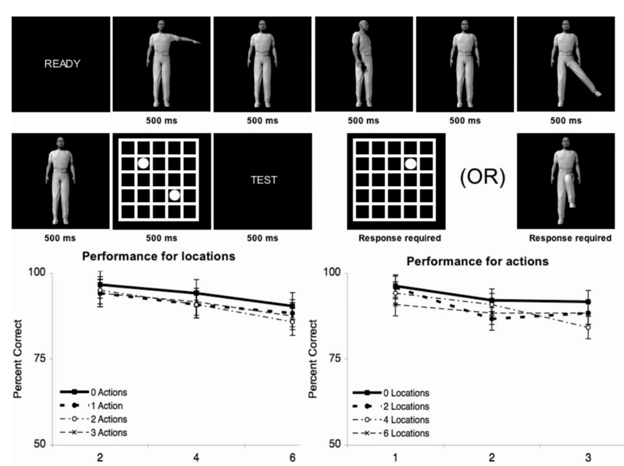

Figure 7. Schematic illustration of a trial and performance for Experiment 7 when participants needed to remember both action information and spatial locations. This example depicts a location change and an action change. Error bars represent 95% confidence intervals for within-subject designs as described by Masson and Loftus (2003).

four, six locations) and presence of load (zero actions vs. one, two, three actions) revealed a main effect of set size only, $F(2, 9) = 5.80$, $p = .01$, $h_p^2 = .39$. The main effect of load, $F(1, 9) = 3.54$, $p = .09$, $h_p^2 = .28$, and the interaction, $F(2, 9) = .03$, $p = .97$, $h_p^2 = .00$, were not significant.

Memory for actions. The ANOVA with variables of set size (one, two, three actions) and load (two, four, six locations) revealed a significant main effect of set size, $F(2, 9) = 4.25$, $p = .03$, $h_p^2 = .32$. The main effect of load, $F(2, 9) = .19$, $p = .83$, $h_p^2 = .02$, and the interaction, $F(4, 9) = 1.29$, $p = .29$, $h_p^2 = .13$, did not approach significance. Thus, working memory for actions is independent of the number of spatial locations maintained in memory. Furthermore, an ANOVA with variables of set size (one, two, three actions) and presence of load (zero locations vs. two, four, six locations) revealed a main effect of set size only, $F(2, 9) = 7.40$, $p = .005$, $h_p^2 = .45$. Unlike in Experiment 4, the effect of load was not significant, $F(1, 9) = 3.01$, $p = .12$, $h_p^2 = .25$. The interaction was also not significant, $F(2, 9) = .25$, $p = .78$, $h_p^2 = .03$. There was no impairment on memory for actions when participants were also required to remember spatial locations.

Experiment 7 provides a conceptual replication of the finding that memory for actions and memory for spatial locations are distinct (Smyth et al., 1989; Smyth & Pendleton, 1988). Furthermore, it extends this finding by showing that memory for one type of information is independent from manipulations in the memory load for the other type of information.

It is interesting that memory for actions and locations is independent given that observed actions consist of body parts changing location. This suggests that when actions are stored in memory, they are packaged into representational units containing a type of spatial information that is not directly supported by spatial working memory (see Smyth et al., 1989; Smyth & Pendleton, 1988). This observation is supported by studies showing that different neural substrates are recruited for processing information about actions and locations—for example, viewing actions activates mirror neuron areas in the prefrontal motor cortex (see Rizzolatti, Fogassi, & Gallese, 2001), whereas memory for locations activates an area in the superior frontal sulcus (Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998).

To summarize, Experiments 1–7 show that working memory does not consist of a general visual memory system for retaining different types of visual information. Rather, it consists of specialized systems that retain information about actions, objects, and locations. In the final experiment, I tested whether the action component is specialized for memory for bodily actions or motion events or whether it supports memory for a variety of event types more generally. The experiment was identical to Experiment 6, except the objects were presented sequentially in the same spatial location. It was important to present the objects in the same spatial location for two reasons. First, when objects are presented sequentially in different spatial locations, it creates the appearance of apparent motion. A presentation yielding apparent motion is unsuitable for testing whether this system supports memory for both motion and nonmotion events, and therefore it was necessary to use a presentation in which objects could be presented sequentially over time without yielding apparent motion. Second, a recent neuroimaging study has shown that different neural substrates are activated when objects are presented simultaneously in different spatial locations compared with sequentially in the same spatial location (Xu & Chun, 2005). By using these same presentation types, it was possible to provide preliminary insight into the neural substrates supporting working memory for actions.

Experiment 8 and Experiments 5 and 6 were identical in terms of the object properties that needed to be retained, but in Experiment 8 the information was presented sequentially rather than simultaneously. If the working memory system for observed actions is specialized for retaining bodily actions, then participants should show the same pattern of performance as in Experiments 5 and 6. However, if common working memory processes are recruited for storing information about other types of events, such as the nonmotion color changing events created when objects appear sequentially in the same spatial location, then in Experiment 8 memory for objects should interfere with memory for actions.

Experiment 8

Method

Ten new participants (male: 4; female: 6) took part in this experiment. Experiment 8 was identical to Experiment 6, except the sample objects were presented sequentially in the center of the screen rather than simultaneously in distinct spatial locations. Each object was presented for 500 ms. See Figure 8 for a schematic illustration of a trial.

Results and Discussion

Memory for objects. The ANOVA with variables of set size (two, four, six objects) and load (one, two, three actions) revealed a significant main effect of set size, $F(2, 9) = 16.24$, $p < .001$, $h_p^2 = .64$. The main effect of load, $F(2, 9) = .15$, $p = .87$, $h_p^2 = .02$, and the interaction, $F(4, 9) = .33$, $p = .86$, $h_p^2 = .04$, did not approach significance. The ANOVA with variables of set size (two, four, six objects) and presence of load (no load vs. one, two, three actions) revealed a main effect of set size, $F(2, 9) = 21.56$,

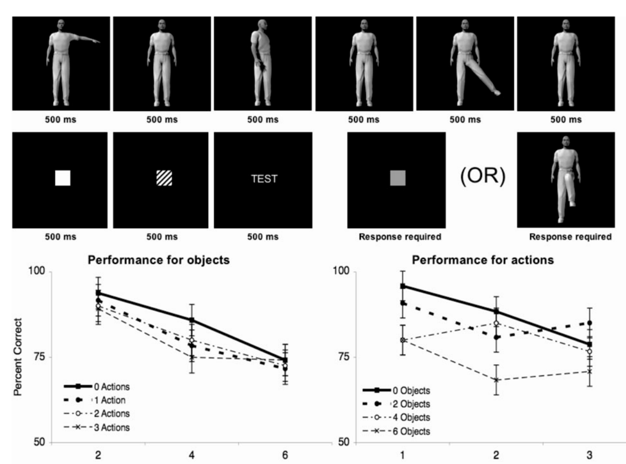

Figure 8. Schematic illustration of a trial and performance for Experiment 8 when the objects were presented sequentially in the same spatial position. This example depicts an object change and an action change. Error bars represent 95% confidence intervals for within-subject designs as described by Masson and Loftus (2003).

$p < .001$, $\eta_p^2 = .71$. The main effect of presence of load was nearly significant, $F(1, 9) = 3.83$, $p = .08$, $\eta_p^2 = .30$. The interaction was not significant, $F(2, 9) = 2.07$, $p = .16$, $\eta_p^2 = .19$).[3]

Memory for actions. The ANOVA with variables of set size (one, two, three actions) and load (two, four, six objects) revealed a significant main effect of load, $F(2, 9) = 8.71$, $p = .002$, $\eta_p^2 = .49$, and a significant main effect of set size $F(2, 9) = 3.65$, $p = .05$, $\eta_p^2 = .29$. The interaction was not significant, $F(4, 9) = 2.03$, $p = .11$, $\eta_p^2 = .18$. Furthermore, the ANOVA with variables of set size (one, two, three actions) and presence of load (zero objects vs. two, four, and six objects) revealed main effects of set size, $F(2, 9) = 16.71$, $p < .001$, $\eta_p^2 = .65$, and presence of load, $F(1, 9) = 16.32$, $p = .003$, $\eta_p^2 = .65$, as well as a significant interaction between set size and load, $F(2, 9) = 6.04$, $p = .01$, $\eta_p^2 = .40$. Unlike in Experiments 5 and 6, there was significant interference of memory for objects on memory for actions—when objects are presented sequentially, rather than simultaneously, working memory requires resources from the system supporting memory for bodily actions.

One possibility is that memory for actions was impaired after observing greater numbers of objects because greater numbers of objects required a longer presentation time, resulting in decay of the action information. However, Experiment 1 shows that information decay cannot be the source of impairment in Experiment 8 because in the adjusted delay interval condition there was no information decay when participants needed to retain one, two, and three actions for delay intervals longer than those in Experiment 8.

This result is consistent with the possibility that the working memory system for action information also supports memory for other types of sequentially presented information. However, at this point, it is impossible to specify the exact nature of the observed interference between memory for actions and memory for sequentially presented objects. One possibility is that information about actions and sequentially presented objects compete for a single capacity-limited memory store. An alternative is that actions and sequentially presented objects are ultimately stored in separate subsystems, with inferences resulting from other capacity-limited processes, such as consolidation (see Logie, 1995) or computations for remembering the order in which items are presented. Currently, studies are being conducted to test among these possibilities.

General Discussion

The goal of the present study was to characterize the nature of working memory for observed actions. The first experiment demonstrates that it is possible to retain information about only two or three actions at one time, showing that working memory for actions is highly capacity limited. The second experiment demonstrates that it is possible to retain the same number of longer actions as shorter actions, showing that the storage capacity of working memory is determined by the number of actions rather than by the total duration of motion. The third experiment shows that the storage capacity of working memory is similar for different action properties, and Experiment 4 shows that it is possible to retain nine properties distributed across three actions almost as well as three properties distributed across three actions. Thus, working memory stores integrated action representations rather than individual properties. Experiments 5 and 6 show that it is possible to retain both two or three actions and three or four objects at one time, showing that working memory consists of distinct systems for retaining information about objects and actions. Experiment 7 shows that working memory for actions and working memory for spatial locations are independent. Finally, Experiment 8 shows that working memory for actions and working memory for sequentially presented objects recruit some type of common capacity-limited process. Together, this pattern of data provides evidence for a previously undocumented system in working memory for retaining information about actions (and potentially other types of visual events as well).

This study raises the question of what counts as an action from the perspective of working memory. Human actions consist of several sub-acts embedded within broader actions—for example, *drinking* involves sub-acts of reaching out, grasping the glass, moving it toward the mouth, and tilting the glass. Similarly, the actions tested here can be divided into smaller sub-acts as well. Is it these sub-acts or the broader action that are the basis of the units stored in working memory? Although this study was not designed to address this question directly, this method could be ideal for investigating the nature of the action representations stored in working memory by testing how the capacity of working memory for actions changes as a function of the available parsing information, such as motion and stasis (Wynn, 1996), the agent's intentions (Baldwin, Baird, Saylor, & Clark, 2001; Zacks & Tversky, 2001), causal relationships, tangent discontinuities in motion (Sharon & Wynn, 2000), and long-term memory categories (Olsson & Poom, 2005).

Implications for Current Models of Working Memory

These studies have important implications for current models of working memory. First, it is possible to retain two to three actions at one time, independent of the number of properties that need to be retained for each action. This pattern is consistent with previous studies showing that observers can retain between three and four objects at one time (Cowan, 2001; Jiang et al., 2000; Luck & Vogel, 1997; Pashler, 1988), independent of the number of simple features that must be encoded for each object (Luck & Vogel, 1997; Vogel et al., 2001). Thus, the rules that govern the storage of visual information about objects and observed actions are general principles of visual working memory rather than specific principles applying to the type of visual entity being processed.

Second, these studies show that working memory consists of multiple systems for retaining different types of visual information. Previous research shows that visual working memory can be divided into separate systems for retaining information about objects and spatial locations (Darling, Della Sala, Logie, & Cantagallo, 2006; Logie, 1995) as well as spatial locations and actions (Smyth et al., 1989; Smyth & Pendleton, 1988). The present study

[3] For the object trials in Experiment 5, there were approximately two times as many misses as false alarms. In Experiments 6–8, however, when only a single object or spatial location was presented in test, false alarms were approximately 2.5 times as common as misses. This may have resulted because in Experiment 6 the test object appeared in a new location, and also in Experiment 6 and Experiment 7 the test object and dot location were presented in isolation. Both of these variables could have led participants to occasionally falsely indicate that there was a change.

shows that visual working memory also consists of distinct systems for retaining information about objects and actions. Thus, visual working memory consists of three separate components for retaining information about objects, locations, and actions. Moreover, working memory for object and action information operate by common storage principles.[4] Thus, like our perceptual system, which consists of distinct processes that analyze input in the same way (e.g., the population coding of frequency in vision and audition), working memory has evolved common solutions to different problems, forming a series of distinct, yet computationally similar systems for retaining different types of visual information.

Current models of working memory are unable to explain these findings without significant modification. As discussed in the introduction, Baddeley (1986) proposed that visual information is stored in a specialized visual subsystem, which has been further divided into separate components for visual and spatial information. The present results show that memory for actions is separate from memory for object and spatial information, suggesting that the visual subsystem consists also of a third component for retaining information about observed actions. More recently, Baddeley (2000) proposed the existence of an episodic buffer, a capacity-limited multimodal memory store that has binding as one of its principle functions. Future studies could investigate whether working memory for actions recruits this hypothesized buffer by asking whether the binding of action properties requires general executive processes proposed to support the episodic buffer. This inquiry would be particularly interesting given that binding visual features to object representations does not require general executive processes (Allen et al., 2006), which suggests that integrated object representations are formed and stored automatically in visual working memory without recruiting the episodic buffer. That is, are action representations, as are object representations, also formed and maintained automatically in the working memory system for actions?

The present findings are also inconsistent with Cowan's (2005) working memory model, which regards working memory as part of long-term memory rather than as a separate system. In this model, representations in working memory are a subset of the representations in long-term memory. At any one time, up to four representations in long-term memory can be selected with an attentional focus, and, according to the theory, it is this attentional focus that results in the three-to-four-item capacity limit observed in object memory tasks. If this were true, then it should be possible to retain a total of three or four objects and actions in working memory simultaneously, with memory for objects and actions competing for the capacity-limited resources of attention. In contrast, the present study shows that it is possible to retain both three or four objects and two or three actions simultaneously, with little to no interference between memory for these different types of information. This pattern of results is difficult to explain without appealing to separate subsystems in working memory; thus, working memory representations are not solely long-term memory representations selected by attention.

Implications for the Neurobiological Mechanisms That Encode Observed Actions

This study places significant constraints on the contents of working memory for observed actions as well as on the underlying neurobiological mechanisms supporting the temporary storage of observed actions. Specifically, a complete description of an observed action requires that multiple types of properties (e.g., type of action, duration, location of the action on the body) be bound into an integrated action representation. Experiments 3 and 4 show that it is these integrated representations, rather than the individual properties, that are stored in working memory. Thus, a neurobiological mechanism is needed for keeping the properties of an action bound together in working memory. As suggested by Vogel, Woodman, and Luck (2001), with regard to the storage of object information, this could be accomplished by the use of temporally synchronized firing among the neurons that code or represent the properties of an action, forming what Hebb (1949) called a *cell assembly*. The neurons within a cell assembly fire at the same temporal pattern as each other but asynchronously with other cell assemblies. The neurons thus have two output values, one that indicates the presence of the coded property and a second that indicates which action is being coded by the neuron, allowing multiple properties to be bound into integrated action representations. This neural mechanism can also account for the limited capacity of working memory for observed actions because as the number of encoded actions increases there will be more accidental correlations between the neurons that code different actions, limiting the ability to resolve distinct action representations.

Furthermore, the dissociation between memory for objects presented simultaneously in separate spatial locations versus sequentially in the same spatial location has also been found in a recent neuroimaging study (Xu & Chun, 2005). When objects are presented simultaneously in different spatial locations, the inferior intraparietal cortex (IPS), the superior IPS, and the lateral occipital complex (LOC) all respond to changes in capacity. However, when objects are presented sequentially in the same spatial location, only the superior IPS and the LOC respond to changes in capacity. Thus, the role of the inferior IPS is likely to maintain spatial attention over objects. In contrast, the superior IPS and the LOC respond to changes in capacity for both simultaneous presentation in different spatial locations, which requires resources from working memory for objects (as shown by Experiments 5 and 6) as well as sequential presentation in the same spatial location, which requires resources from working memory for objects and

[4] The present study shows that working memory for observed actions is subject to a primacy effect. However, previous studies show that working memory for sequentially presented objects is subject to a recency effect (e.g., Phillips & Christie, 1977), which was also found in Experiment 8. When presented with a test object that was the same as an object in the sample sequence, participants were more likely to remember that object when it appeared in the final position of the sequence (first position: 60%; second position: 43%, third position: 50%; fourth position: 46%; fifth position: 63%; sixth position: 96%). Thus, although the object and action components of working memory both store integrated representations in memory stores with similar capacities, they also differ in some respects. Visual working memory for object information may be subject to a recency effect because object information needs to be encoded and replaced relatively quickly and automatically to maintain a coherent visual experience during brief visual interruptions such as saccades, resulting in better memory for recently observed objects. In contrast, a stable visual experience does not depend on encoding action information. Thus, action information may be encoded through more active processes and may be less susceptible to replacement by new information, resulting in better memory for events occurring earlier in the sequence.

working memory for actions (as shown by Experiment 8). This pattern of data is consistent with two possibilities. First, the superior IPS and the LOC may support both object and action working memory. Second, the observed change in activation as a function of capacity for sequentially presented objects in the same spatial location could reflect contributions from the object component of working memory, whereas other neural substrates support working memory for actions. Currently, studies are being conducted with neuroimaging methods to directly test the shared and unique neural substrates of working memory for actions.

In summary, this study provides evidence for a previously undocumented system in working memory for retaining information about actions. This system operates by the same storage principles as visual working memory for object information, with a storage capacity of between two and three integrated action representations. Thus, despite the behavioral and potential neurobiological similarities between how objects and actions are retained, working memory has evolved distinct systems for retaining these different types of visual information. Future studies will investigate the nature of the working memory system that retains information about actions by examining the units over which it operates, how it parses visual experience into these units, and the processes through which the brain integrates information stored in different working memory systems.

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Received October 5, 2006
Revision received April 30, 2007
Accepted May 1, 2007 ■