

Visual Long-Term Memory Stores High-Fidelity Representations of Observed Actions

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Abstract

The ability to remember others' actions is fundamental to social cognition, but the precision of action memories remains unknown. To probe the fidelity of the action representations stored in visual long-term memory, we asked observers to view a large number of computer-animated actions. Afterward, observers were shown pairs of actions and indicated which of the two actions they had seen for each pair. On some trials, the previously viewed action was paired with an action from a different action category, and on other trials, it was paired with an action from the same category. Accuracy on both types of trials was remarkably high (81% and 82%, respectively). Further, results from a second experiment showed that the action representations maintained in visual long-term memory can be nearly as precise as the action representations maintained in visual working memory. Together, these findings provide evidence for a mechanism in visual long-term memory that maintains high-fidelity representations of observed actions.

Keywords

long-term memory, visual memory, memory, cognitive ability, visuospatial ability

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Humans are incredibly social. Every day, people observe a dizzying array of actions performed by other individuals, in contexts that include cooperation, violence, territorial defense, competition, and parental care. The ability to remember these actions is at the core of humans' capacity to engage in normal social interactions. In the study reported here, we probed the precision of action memory, examining whether visual long-term memory stores detailed representations of observed actions.

Many sociocognitive abilities are supported by representations of observed actions maintained in long-term memory. People use memories of observed actions to learn motor skills and imitate actions (e.g., Brown & Robertson, 2007; Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2010; Krakauer & Shadmehr, 2006; Muellbacher et al., 2002; Robertson, Press, & Pascual-Leone, 2005), recognize other people (e.g., Cutting & Kozlowski, 1977; Hill & Pollick, 2000; Troje, Westhoff, & Lavrov, 2005), infer intentions (e.g., Cohen, Pascual-Leone, Press, & Robertson, 2005; Robertson, 2009; Robertson & Cohen, 2006), and predict other individuals' future behavior.

Critically, people's accuracy in performing these functions depends on the fidelity of the visual action representations maintained in memory. During imitation, for example, individuals observe an action, store the details of that action in memory, and later reproduce the action, attempting to match

their motor actions to the visual representation stored in memory. Because imitation occurs after the action has been observed, the precision of the visual representation will directly constrain the precision of imitation. If long-term memory stores low-fidelity representations of actions, then imitators will be able to reproduce actions only at that same low level of fidelity. Indeed, imitation is one of the primary ways of acquiring knowledge and skills from other people; thus, the precision of imitation also constrains the spread of behavioral traditions in nonhuman animals and the spread of cumulative culture in humans. However, little is known about the fidelity of action representations maintained in long-term memory.

Previous studies have examined long-term memory for actions in contexts that include social conformity, aging, unconscious transference, statistical learning, and source monitoring (e.g., Earles, Kersten, Curtayne, & Perle, 2008; Endress

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& Wood, 2011; Goff & Roediger, 1998; Kersten & Earles, 2010; Kersten, Earles, Curtayne, & Lane, 2008; Loftus, 1976; Perfect & Harris, 2003; Ross, Ceci, Dunning, & Togliola, 1994; Wright & Schwartz, 2010). In general, these studies have shown that memories of actions are not always accurate. For example, memories of actions are susceptible to social influences (Wright & Schwartz, 2010) and to agent-action binding errors, in which observers remember having seen an action but fail to remember the acting agent (Earles et al., 2008; Kersten & Earles, 2010; Kersten et al., 2008; Loftus, 1976; Perfect & Harris, 2003; Ross et al., 1994). These findings have important implications for eyewitness testimony because they call into question the reliability of people's ability to remember others' actions. More generally, they suggest that long-term memory for actions lacks detail, storing only the gist of what has been seen. Although observers might remember the gist of an action (e.g., "I saw a jumping action, not a kicking action"), they may not remember the specific details (e.g., "I saw that specific jumping action").

Although these studies have provided evidence that action memories are stored with low fidelity, other studies have shown that long-term memory can store visual items with high fidelity. Specifically, researchers have used the two-alternative forced-choice method to examine the storage capacity of long-term memory for objects and scenes (e.g., Brady, Konkle, Alvarez, & Oliva, 2008; Konkle, Brady, Alvarez, & Oliva, 2010a, 2010b). These studies, as well as earlier studies (e.g., Hollingworth, 2004, 2005; Shepard, 1967; Standing, 1973; Standing, Conezio, & Haber, 1970) have shown that visual long-term memory has a massive storage capacity for the details of visual images. For example, after viewing thousands of objects, participants can distinguish study objects from new objects drawn from the same basic-level category as the study objects (Brady et al., 2008).

Why do some studies suggest that long-term memory stores low-fidelity representations of observed actions, whereas other studies suggest that long-term memory stores high-fidelity representations of objects and scenes? One possibility is that different kinds of entities are stored in different ways: Observed actions might be stored with low fidelity, whereas objects and scenes might be stored with high fidelity. This seems plausible, given that actions differ from objects and scenes in many respects (Wynn, 1996). For instance, both objects and scenes endure over time, whereas actions endure only temporarily, existing at distinct points in time. Consequently, for objects and scenes, long-term memory encodes information that is distributed over space, whereas for actions, long-term memory must encode dynamic information that is distributed over both space and time.

Alternatively, visual long-term memory might store many kinds of entities, including observed actions, with high fidelity. Preliminary support for this hypothesis has come from studies showing that humans can recognize their friends on the basis of how they move in point-light displays (Cutting & Kozlowski, 1977; see also Stevens, Ginsborg, & Lester, 2011).

Previous studies may have failed to reveal high-fidelity action representations because the methods used were not sufficiently sensitive—for example, many of the studies cited earlier tested action memory by probing agent-action binding, a method that would underestimate the fidelity of action representations if agent information and action information were stored separately in visual long-term memory.

To distinguish between these two possibilities, we probed the fidelity of action representations stored in long-term memory by using the same two-alternative forced-choice method that has previously been used to reveal high-fidelity representations of objects and scenes in long-term memory (Brady et al., 2008; Konkle et al., 2010a, 2010b).

In the study phase of Experiment 1, participants viewed a large number of computer-animated actions (see Video S1 in the Supplemental Material available online for exemplars). In a subsequent test phase, they were then shown pairs of actions and indicated for each pair which of the two actions they had seen. Critically, we presented precisely controlled computer-animated actions: All actions were performed by the same agent, were displayed from the same viewpoint, lasted for the same amount of time, and involved no props. Further, the stimuli set included many exemplars from each of five categories of actions. The actions consisted of jumps, turns, bends, arm raises, and crouches (Fig. 1). Successful recognition therefore required storing detailed representations of the actions as opposed to remembering only their gist.

In addition, to examine the role of exposure time in building accurate representations of actions in long-term memory, we varied the number of times each action was observed. Specifically, participants observed each action presented in the study phase five times (five-observations condition), three times (three-observations condition), or one time (one-observation condition). We provided participants in the three-observations condition with 3 s of exposure to each study action, following previous studies of visual long-term memory in which observers were presented with each object or scene for 3 s (Brady et al., 2008; Konkle et al., 2010a, 2010b).

Experiment 1

Method

Participants. Twenty-four college students (8 males, 16 females; mean age = 19 years, $SD = 0.97$) with normal or corrected-to-normal vision participated in return for credit toward a course requirement. Eight participants were randomly assigned to each of the three conditions. Informed consent was obtained.

Stimuli. The stimuli set contained 80 action animations generated with Poser animation-creation software (Version 7; Smith Micro Software, Aliso Viejo, CA). The acting agent subtended $9.9^\circ \times 3.9^\circ$ of visual angle at the center of a 17-in. computer screen. All actions had the same duration (1,000 ms) and frame rate (30 frames per second), were performed by the same

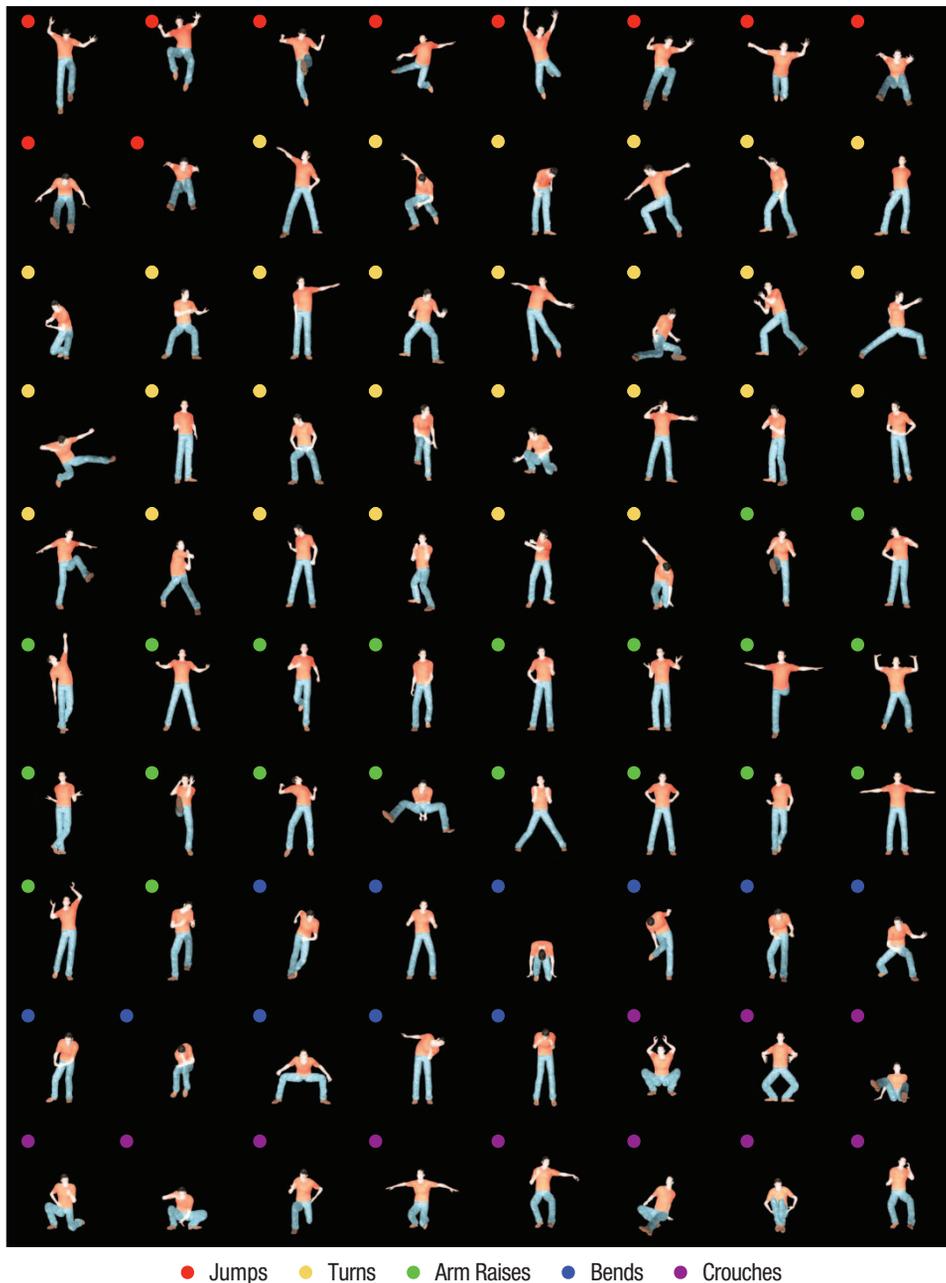


Fig. 1. Images of still frames from the stimuli used in Experiment 1. The stimuli consisted of 80 animations of movements. The images show each of the 80 movements' maximal deviation from a neutral position. Colored dots indicate categories of movements: jumps, turns, arm raises, bends, and crouches.

agent, and were displayed from the same viewpoint (see Video S1 for examples). In each animation, the actor started and ended in a neutral standing position, and the actor's position reached its maximal deviation from the neutral position at the 15th frame.

Procedure. The experiment consisted of a study phase and a test phase. In the study phase, participants viewed 40 actions randomly selected from the stimuli set depicted in Figure 1. Each trial began with a 1,000-ms presentation of a black

screen, followed by an action animation, which was in turn followed by another 1,000-ms presentation of a black screen. In the different conditions, the actions in the study phase were displayed five times, three times, or one time. A 1,000-ms presentation of a black screen separated each presentation of an action. To ensure that participants maintained their attention, we had them perform a repeat-detection task during the study phase (Brady et al., 2008). Ten of the 40 actions were presented on two trials in the study phase, with zero, one, two, three, or four trials intervening between the first and second

presentations. After the presentation of each action, the phrase “Old or New” appeared on the screen, prompting participants to indicate whether the action was a repeated action or a new action. Participants responded without time pressure.

The test phase began approximately 1 min after the study phase. In the test phase, participants performed a two-alternative forced-choice test. Two actions were presented on the screen: one previously viewed action and one new action (the foil action). The foil action could be an action from a different category than the previously viewed action (different-category comparison) or an action from the same category (same-category comparison). Averaged across participants, different-category comparisons accounted for 74% of the trials, and same-category comparisons accounted for 26% of the trials.

Each test trial began with a 1,000-ms presentation of a black screen, followed by an action animation presented on the left half of the screen, which, after an interval of 1,000 ms, was replaced by another action animation presented on the right half of the screen. Both the previously viewed action and the foil action were displayed one time. Across all trials, the previously viewed action was presented an equal number of times on the left and right sides of the screen. After observing the second action, participants indicated which action had previously been seen in the study phase by pressing one of two keys on a keyboard. Verbal instructions were provided before the experiment, and written instructions were provided on the screen before each phase of the experiment. Specifically, participants were told that they would see a large number of actions and would then be tested on their ability to remember those actions.

Results and discussion

Results are depicted in Figures 2 and 3. Accuracy was high, with participants correctly recognizing the previously viewed

action on 81% ($SEM = 4\%$) of the trials in the five-observations condition, 80% ($SEM = 3\%$) of the trials in the three-observations condition, and 76% ($SEM = 5\%$) of the trials in the one-observation condition. For trials in which a previously viewed action was paired with a foil action from a different category, participants' rate of accuracy was 81% ($SEM = 5\%$) in the five-observations condition, 80% ($SEM = 2\%$) in the three-observations condition, and 77% ($SEM = 5\%$) in the one-observation condition (see Fig. 2). For trials in which a previously viewed action was paired with a foil action from the same category, participants' rate of accuracy was 82% ($SEM = 4\%$) in the five-observations condition, 79% ($SEM = 6\%$) in the three-observations condition, and 71% ($SEM = 5\%$) in the one-observation condition (see Fig. 2). Across all conditions, the accuracy rates for different-category comparisons and for same-category comparisons did not vary significantly—five-observations condition: $F(1, 7) = 0.03$, $p = .86$, $\eta_p^2 = .01$; three-observations condition: $F(1, 7) = 0.02$, $p = .90$, $\eta_p^2 = .01$; one-observation condition: $F(1, 7) = 2.50$, $p = .16$, $\eta_p^2 = .26$.

Across all conditions and both types of comparisons, the accuracy rates were significantly higher than chance level (50%)—five-observations condition, different-category comparison: $t(7) = 7.92$, $p < .001$; five-observations condition, same-category comparison: $t(7) = 4.05$, $p < .01$; three-observations condition, different-category comparison: $t(7) = 15.51$, $p < .001$; three-observations condition, same-category comparison: $t(7) = 5.16$, $p = .001$; one-observation condition, different-category comparison: $t(7) = 5.60$, $p = .001$; one-observation condition, same-category comparison: $t(7) = 3.59$, $p < .01$. An analysis of variance (ANOVA) with the factors of comparison type (different-category comparison vs. same-category comparison) and condition (five observations, three observations, one observation) revealed no main effect of comparison type, $F(1, 21) = 1.14$, $p = .30$, $\eta_p^2 = .05$, no main effect of condition,

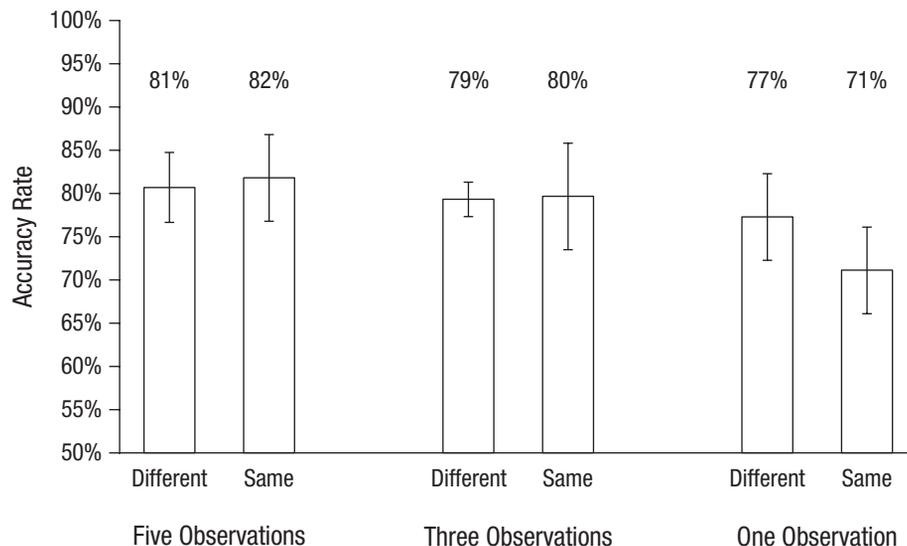


Fig. 2. Results from Experiment 1: mean percentage of trials on which participants recognized study actions as a function of condition (five observations, three observations, or one observation) and types of actions compared (different category or same category). Error bars denote standard errors.

$F(2, 21) = 0.72, p = .50, \eta_p^2 = .06$, and no interaction between the two factors, $F(2, 21) = 0.61, p = .55, \eta_p^2 = 0.06$.

Further, accuracy did not vary as a function of the number of exemplars that needed to be remembered from each action category (Fig. 3). Accuracy rates for same-category comparisons were high irrespective of whether the old action belonged to an action category that had a small (e.g., 2) or large (e.g., 18) number of exemplars in the study set. The correlation between accuracy and the number of exemplars in the study set was not significant in any of the conditions—five-observations condition: $r = .16, p = .62$; three-observations condition: $r = -.29,$

$p = .34$; one-observation condition: $r = .12, p = .69$.¹ Similarly, accuracy rates for different-category comparisons were high irrespective of whether the foil action belonged to an action category that had a small or a large number of exemplars in the study set. The correlation between performance and the number of exemplars in the study set was not significant in any of the conditions—five-observations condition: $r = -.25, p = .38$; three-observations condition: $r = -.05, p = .86$; one-observation condition: $r = .46, p = .12$.

Finally, performance on the repeat-detection task in the study phase also revealed accurate memory for actions. Accuracy was

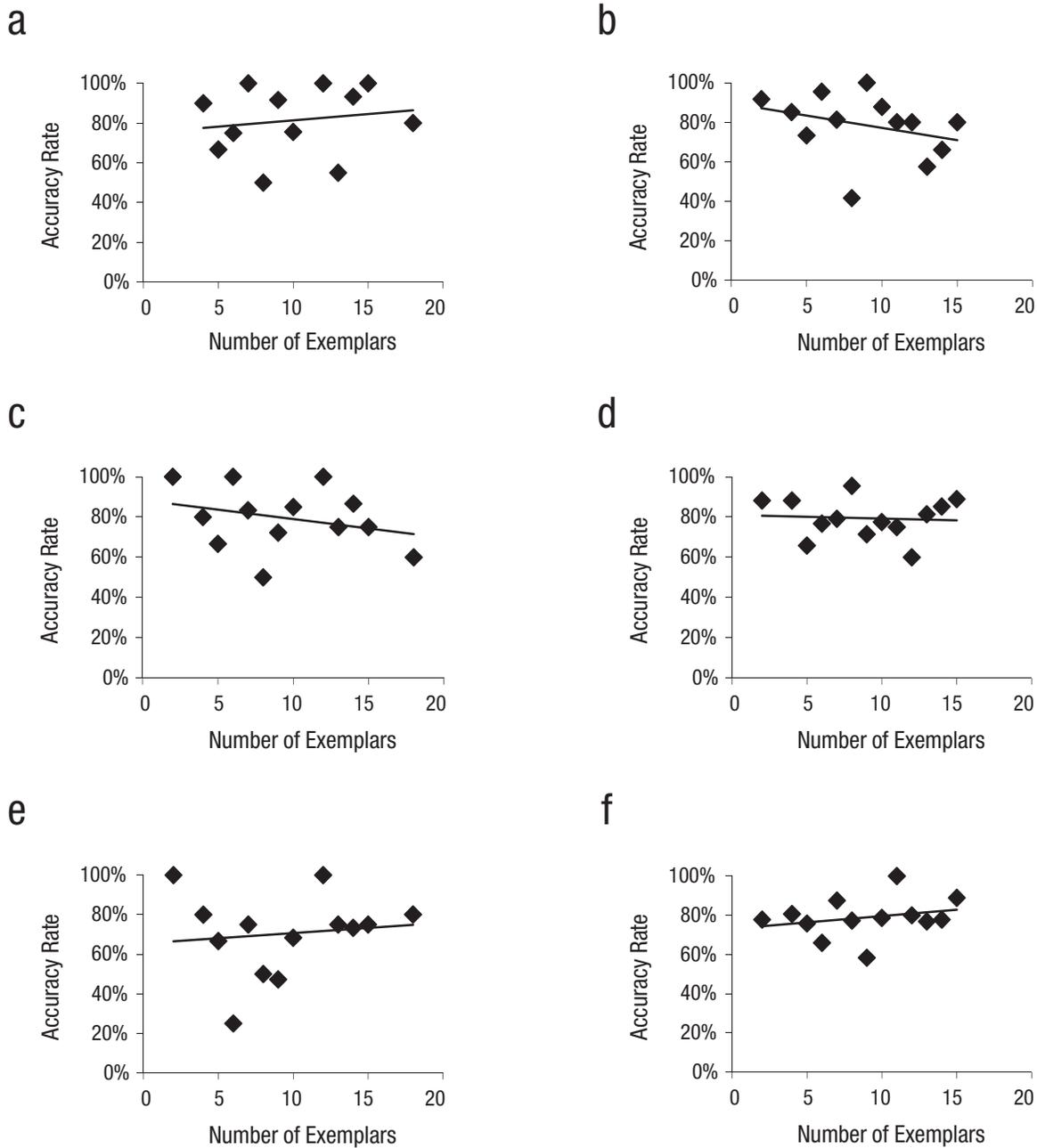


Fig. 3. Results from Experiment I: mean percentage of trials on which participants recognized study actions as a function of the number of same-category exemplars that needed to be remembered from the study set. Results are shown separately for the five-observations condition (a, b), the three-observations condition (c, d), and the one-observation condition (e, f). The graphs on the left show accuracy as a function of the number of exemplars from the same action category as the old test action in same-category comparisons. The graphs on the right show accuracy as a function of the number of exemplars from the same action category as the new foil test action in the different-category comparisons.

90% ($SEM = 2\%$) in the five-observations condition, 89% ($SEM = 3\%$) in the three-observations condition, and 81% ($SEM = 3\%$) in the one-observation condition.

Experiment 2

The results from Experiment 1 provide evidence that visual long-term memory can store detailed representations of observed actions. In Experiment 2, we further assessed the fidelity of the action representations maintained in long-term memory by using a recall-like paradigm (e.g., Zhang & Luck, 2008). Specifically, during each trial in the test phase, 10 actions were presented that differed only in their range of motion, and participants indicated which of those actions was the study action (Fig. 4a). If an action has been stored with high precision, the participant should select a test action with a similar range of motion as the study action. If an action has been stored with low precision or has not been stored at all, then the participant will have no information about the action's range of motion, and his or her response should be random.

In addition, we wanted to compare the fidelity of the action representations stored in visual long-term memory with the fidelity of the action representations stored in visual working memory. To do so, we assigned participants to one of two conditions. In the immediate-test condition, the presentation of each study action was followed immediately by the presentation of a corresponding set of test actions. Thus, participants needed to maintain each study action for just a few seconds in visual working memory. In the delayed-test condition, participants first observed all of the study actions and then observed all of the test actions. Thus, participants needed to maintain all of the study actions in long-term memory before responding on the test trials.

Method

Participants. Twenty volunteers (5 males, 15 females; mean age = 29 years, $SD = 3.0$) participated. Ten participants were randomly assigned to each condition.

Stimuli. We tested participants' memory for 12 study actions. For each study action, we created 10 corresponding test actions that were identical to the study action in all respects except for their range of motion (one of the test actions—the target—had the same range of motion as the study action; see Fig. 4a for an illustration of the actions and Video S2 in the Supplemental Material for an example trial). The test actions were displayed in two rows, with five actions in the top row and five in the bottom row. Within each row, the range of motion of each action increased systematically from left to right in equal intervals (ranging between 9° and 15° across the test-action sets). The agent subtended $4.9^\circ \times 1.9^\circ$ of visual angle. In all other aspects, the action animations (e.g., duration, frame rate) were similar to those used in Experiment 1.

Procedure. Each study action was displayed three times. On each test trial, 10 actions, labeled 0 to 9, were displayed at the same time. The actions were presented 20 times; during this time, participants indicated which of the test actions was identical to the study action. For each participant, the study actions were randomly selected from the corresponding sets of test actions.

In the immediate-test condition, a test trial immediately followed each study trial. In the delayed-test condition, participants observed all 12 study actions before completing the 12 test trials. The actions were presented in the same order in the

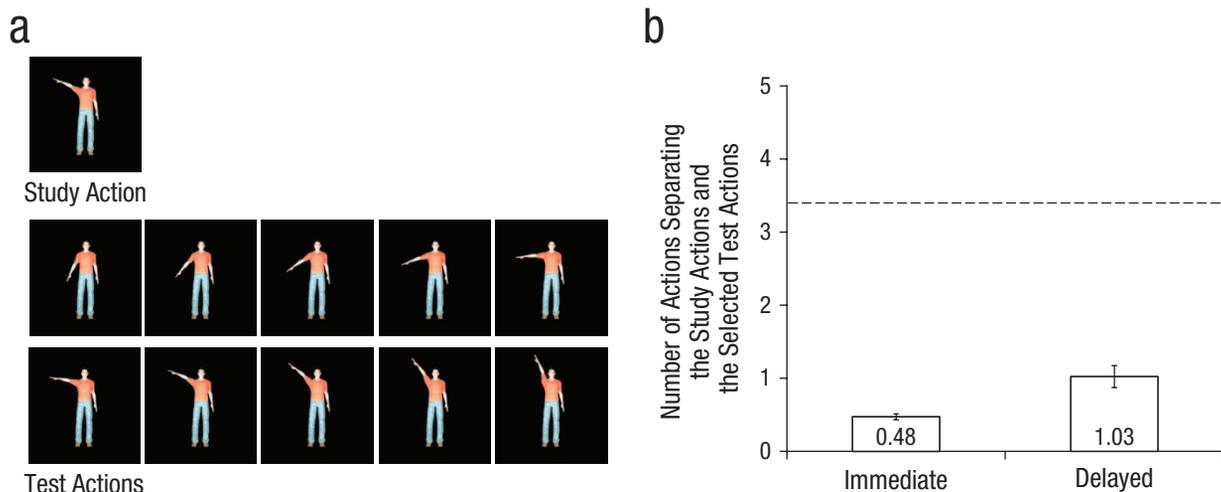


Fig. 4. Schematic illustration of a trial and results from Experiment 2. Participants were shown an animation of a study action and then 10 test animations that differed only in their range of motion; the test actions were presented in two rows simultaneously and positioned according to their range of motion, which increased systematically from left to right in each row in equal intervals. Participants indicated which test action matched the study action. The illustrations here (a) show still frames from an example study action and the corresponding test actions; each frame is from the point at which the action's deviation from a neutral standing position was greatest. The graph (b) shows the average absolute difference between the position of the study action and the position of the selected test action as a function of condition (immediate test vs. delayed test). The dashed line indicates chance performance. Error bars denote standard errors.

study and test phases. Participants completed four practice trials before starting the experiment.

Results and discussion

In the immediate-test condition, participants identified the correct test action on 63% ($SEM = 4\%$) of the trials. In the delayed-test condition, participants identified the correct test action on 43% ($SEM = 5\%$) of the trials. Accuracy in both conditions was significantly higher than chance level (10%)—immediate-test condition: $t(9) = 13.20, p < .001$; delayed-test condition: $t(9) = 6.67, p < .001$. Accuracy differed significantly between these conditions, $t(18) = 3.18, p < .01$.

Next, we analyzed the absolute difference between each study action and the selected test action (Fig. 4b). In the immediate-test condition, on average, participants selected a test action that deviated from the study action by 0.48 test-action positions ($SEM = 0.04$). In the delayed-test condition, on average, participants selected a test action that deviated from the study action by 1.03 test-action positions ($SEM = 0.15$). There was a significant difference between the two conditions, $t(18) = 3.45, p < .01$.

In sum, performance was accurate in both conditions: Participants tended to select either the correct action or a test action with a range of motion similar to that of the study action. Critically, accuracy was only slightly lower in the delayed-test condition than in the immediate-test condition. This indicates that action representations stored in visual long-term memory contain only slightly less detail than action representations that need to be maintained for just a few seconds in visual working memory.

General Discussion

In this study, we probed the fidelity of the action representations stored in visual long-term memory. To do so, we conducted two experiments. In Experiment 1, we used the two-alternative forced-choice method used in previous studies that revealed high-fidelity representations of objects and scenes in long-term memory (e.g., Brady et al., 2008). We also examined the efficiency of this long-term-memory mechanism by presenting each study action five times, three times, or just one time. In all conditions, recognition was remarkably accurate irrespective of whether previously viewed actions were compared with actions from the same category or actions from a different category. Further, accuracy did not vary as a function of the number of same-category exemplars that needed to be remembered. These results indicate that visual long-term memory can store detailed representations of observed actions and can do so with relatively little input (e.g., a single observation of an action). These findings complement those of previous studies showing that long-term memory can store details of other kinds of dynamic stimuli (e.g., walking gaits) after extensive exposure (e.g., Cutting & Kozlowski, 1977).

In Experiment 2, we used a recall-like paradigm to further assess the precision of action memory. To perform

successfully, participants needed to remember the specific range of motion of each study action. Performance was remarkably accurate: Participants tended to select either the correct action (the study action) or a test action with a range of motion similar to that of the study action.

Together, these studies provide an initial assessment of the fidelity of the visual action representations stored in long-term memory. Results showed (a) that action memory is sufficiently precise to distinguish between actions that belong to the same category and (b) that action memory is sufficiently precise to distinguish between actions with ranges of motion that differ by only a few degrees. Thus, contrary to claims that long-term memory stores representations that capture only the gist of actions, our results indicate that action memory can be highly precise.

Additional research is needed, however, to develop a more formal characterization of the fidelity and information capacity of long-term memory for observed actions. For instance, in studies of object memory, researchers have used large-scale experiments (e.g., experiments in which participants needed to remember thousands of items) to estimate the capacity of long-term memory for visual object information (e.g., Brady et al., 2008). In contrast, in the current study, study phases involved the presentation of 40 actions in Experiment 1 and 12 actions in Experiment 2. Critically, in both the earlier large-scale studies and the study reported here, the number of items presented and remembered significantly exceeded the storage capacity of visual working memory; for observed actions, this storage capacity is just two to three movements (Wood, 2007). Thus, we can assume that participants in the present study used a long-term-memory mechanism to remember the actions. Nevertheless, with large-scale experiments, it is possible to estimate the capacity of long-term memory by calculating the numbers of bits of information required to correctly make a decision about which items have been seen and which have not (see Brady et al., 2008; Landauer, 1986). It would be interesting for future studies to use such large-scale methods to estimate the capacity of long-term memory for observed actions.

Our findings suggest that long-term memory does not simply store the gist of observed actions. Why did our study reveal accurate memory for observed actions when previous studies have reported that action memory can be highly inaccurate? Most previous studies that have reported inaccurate memory for actions tested whether observers could remember which agent performed which action (e.g., Earles et al., 2008; Kersten & Earles, 2010; Kersten et al., 2008; Loftus, 1976; Perfect & Harris, 2003; Ross et al., 1994), a task that requires observers to bind agent information and action information in long-term memory. In contrast, our paradigm did not require agent-action binding; it tested memory for actions only. Thus, although memory for actions may be precise, memory for agent-action binding may not be.

Support for this hypothesis comes from studies of visual working memory and from studies examining the neural substrates of agent and action representation. Studies of visual working memory have shown that agent information and

action information are maintained by separate mechanisms (Wood, 2008, 2011). This dissociation leads to a specific pattern of memory errors in which participants can successfully remember individual agents and actions but have considerable difficulty remembering which agent performed which action. Studies examining the neural substrates of agent and action representation have demonstrated a similar dissociation between the processing of agent information and the processing of action information. For instance, viewing images of the human body activates the lateral occipitotemporal area (e.g., 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, 2001).

More generally, this study converges with previous studies showing that visual long-term memory stores detailed representations of objects and scenes (e.g., Brady et al., 2008; Konkle et al., 2010a, 2010b). Visual long-term memory can therefore store visual information with high fidelity both when the information is distributed over space (e.g., objects and scenes) and when the information is distributed over space and time (e.g., observed actions).

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information may be found at <http://pss.sagepub.com/content/by/supplemental-data>

Note

1. One participant in the five-observations condition was excluded from this analysis because the participant's level of accuracy was more than 2 standard deviations from the mean. The correlation was not significant regardless of whether the participant's data were included in the analysis.

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