Short Communication

Integrating actions into object location memory: A benefit for active versus passive reaching movements

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HIGHLIGHTS

- Active reaching movements facilitate object location memory.
- Active movements benefit representation of peripersonal, reachable space.
- Efferent motor commands, in the absence of proprioception, facilitate spatial memory.

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ABSTRACT

We tested whether learning the mapping between objects and their locations is better when actively moving the hand to these locations, to reveal the object, compared to when the hand is passively moved by a robotic manipulandum. Recall of object locations was more accurate in the active compared to passive condition. We also found that recall was less accurate when participant made active movements that were not directed to the object locations. These results indicate that the well-established active exploration advantage for spatial memory extends to location memory for objects within reach. Such active learning is likely important for manipulation tasks.

Object location memory is important for many daily activities and enables us to reach towards remembered objects without conducting a visual search and even in the absence of visual feedback [1]. Object locations are often learned through active movements involved in contacting, manipulating and placing objects in our environment. Such active interaction with objects is known to convey an advantage over passive viewing for the recognition of object identity [2,3] and a benefit of active over passive movement for spatial memory has been demonstrated in animals [4], adult humans [5], and children [6]. An advantage of active over passive exploration for spatial memory of extrapersonal space—which often involves learning the locations of objects (i.e., landmarks) to facilitate spatial memory [7]—has been demonstrated for spatial navigation, path integration, and wayfinding ([7,20,21]; see [8]

for a recent review). In addition, the ability to reproduce pointing movements or arm postures is better these movements or postures are experienced actively rather than passively [9,10].

Object location memory is generally thought to rely on (1) remembering object identities, (2) remembering spatial positions, and (3) binding individual objects onto specific locations [11,12]. When spatial locations are visible, as for example in the card game 'memory' or 'concentration', the first and third processes are critical. The aim of the current study was to test whether there is an advantage of active over passive arm movements when learning mappings between object identities and their visible locations in reachable space, a question that has not been previously addressed.

Previous work has shown that some combination of efferent motor commands and proprioceptive information underlies the active advantage for spatial memory [7]. In the passive condition used in many previous studies, both motor commands and proprioception information are removed (e.g., participant are moved about the environment in a wheelchair) and therefore the relative contributions of these factors are difficult to uncover [8]. In the current study, proprioceptive differences between active and passive

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movement were limited, thereby isolating the motor commands as the main factor that differed between conditions. In the active condition, participants uncovered hidden virtual objects in the horizontal plane by making self-generated reaching movements to various locations while grasping a handle attached to a robotic device. In the passive condition, participants relaxed their arm and allowed the robotic device to move their hand to the targets. We tested the hypothesis that, during subsequent recall, object location memory would be better in the active compared to the passive condition.

We assessed the performance of 24 healthy, right-handed participants (14 females) between 18 and 33 years old. Twelve participants completed Experiment 1 in which an active learning condition was compared to a passive learning condition, and 12 participants participated in a control experiment (Experiment 2) in which the active condition was compared to an active-unlinked condition (described below). A Queen's University ethics committee approved the protocol. While seated, the participant grasped a vertical handle attached to a lightweight planar robotic manipulandum (vBOT, Cambridge University, [13]) that moved in a horizontal plane (Fig. 1A). The participant's forearm was supported by a cuff mounted on air sleds that moved across a glass surface with near-zero friction. Participants viewed visual stimuli in a semi-silvered mirror located halfway between a monitor and the vBOT handle (Fig. 1A). This design allowed the visual stimuli to appear in the same plane in which the vBOT handle moved, and occluded the participant's arm from view. The position of the handle was represented by a circular cursor (hand cursor in Fig. 1B), and was sampled at a rate of 1000 Hz, with a resolution of 0.1 mm, using encoders on the manipulandum.

During training trials (see below), participants actively moved the handle to targets in the active and active-unlinked conditions, whereas, in the passive condition, the robot moved the handle, and thus the participant's hand, along a straight-line minimum jerk reference trajectory (of duration 1000 ms) to each target location, with a stiff damped spring (stiffness of 2000 N/m and viscosity of 10 Ns/m). Although participants were required to generate motor commands to grasp the handle in the passive condition, they did not generate motor commands to move the handle to object locations. The average, scored movement time for the training trials was similar ($t_{11} = 1.59$, $p = .140$) in passive ($M = 817$ ms, $SE = 1$ ms) and active conditions ($M = 948$ ms, $SE = 82$ ms).

In a given block of trials, 10 circular white targets (10 mm radius) were displayed at random distances and angles to the right of the
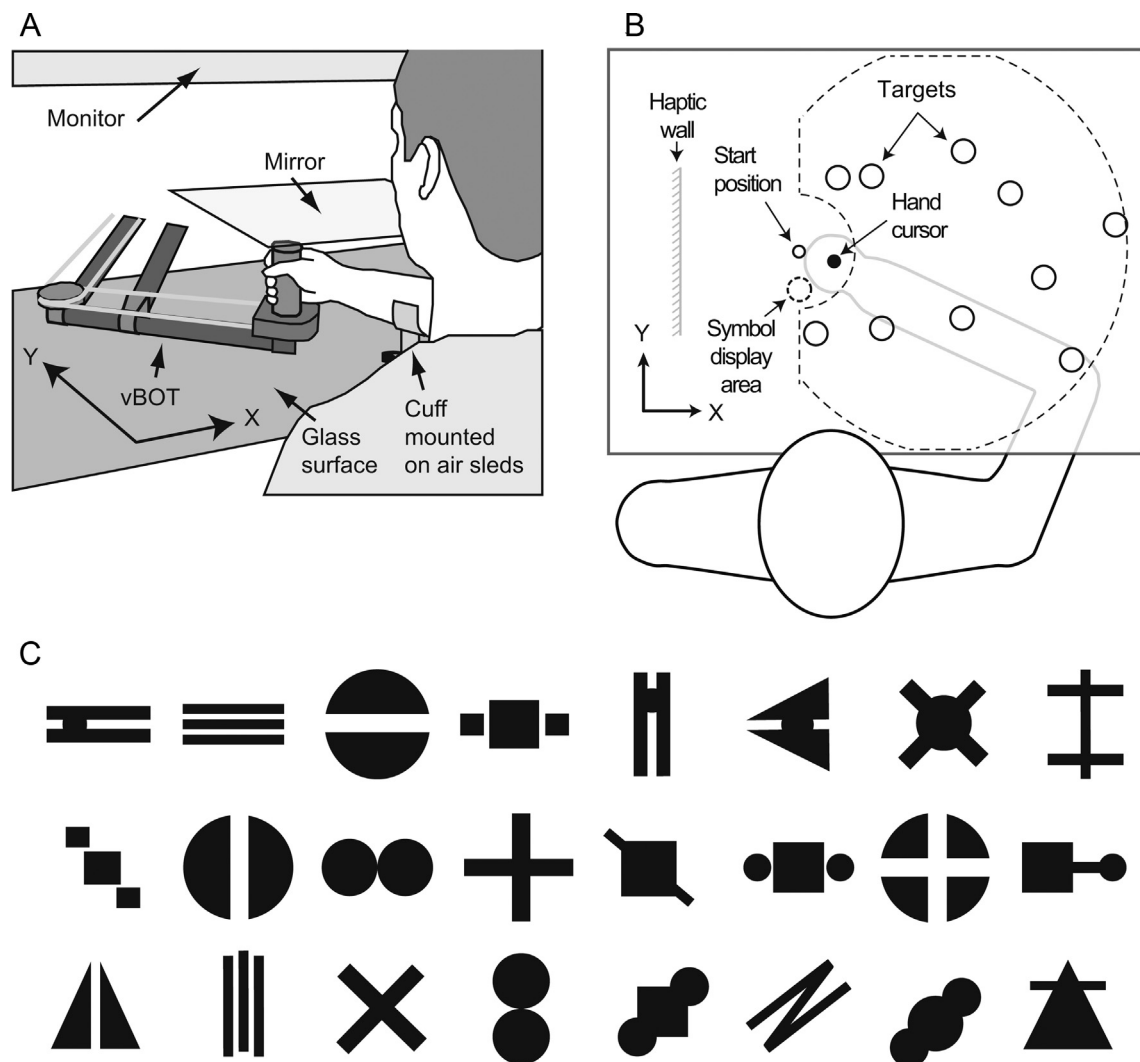

Fig. 1. (A) Illustration of a seated participant gripping the vBOT handle. (B) Aerial view showing the hand start position, cursor representing the hand, and a set of targets randomly positioned within the area denoted by the broken line. In training trials of the active and passive conditions, either the participant or the robot moved the participant's hand from the start position to one of the targets to discover the hidden symbol. In the active-unlinked condition, participants moved from the start position to contact an invisible haptic wall to reveal the symbol hidden at the target location. In test trials, symbols were shown within the symbol display area under the start position, and participants moved to the target at which they remembered seeing each symbol. (C) Symbols hidden by the targets.
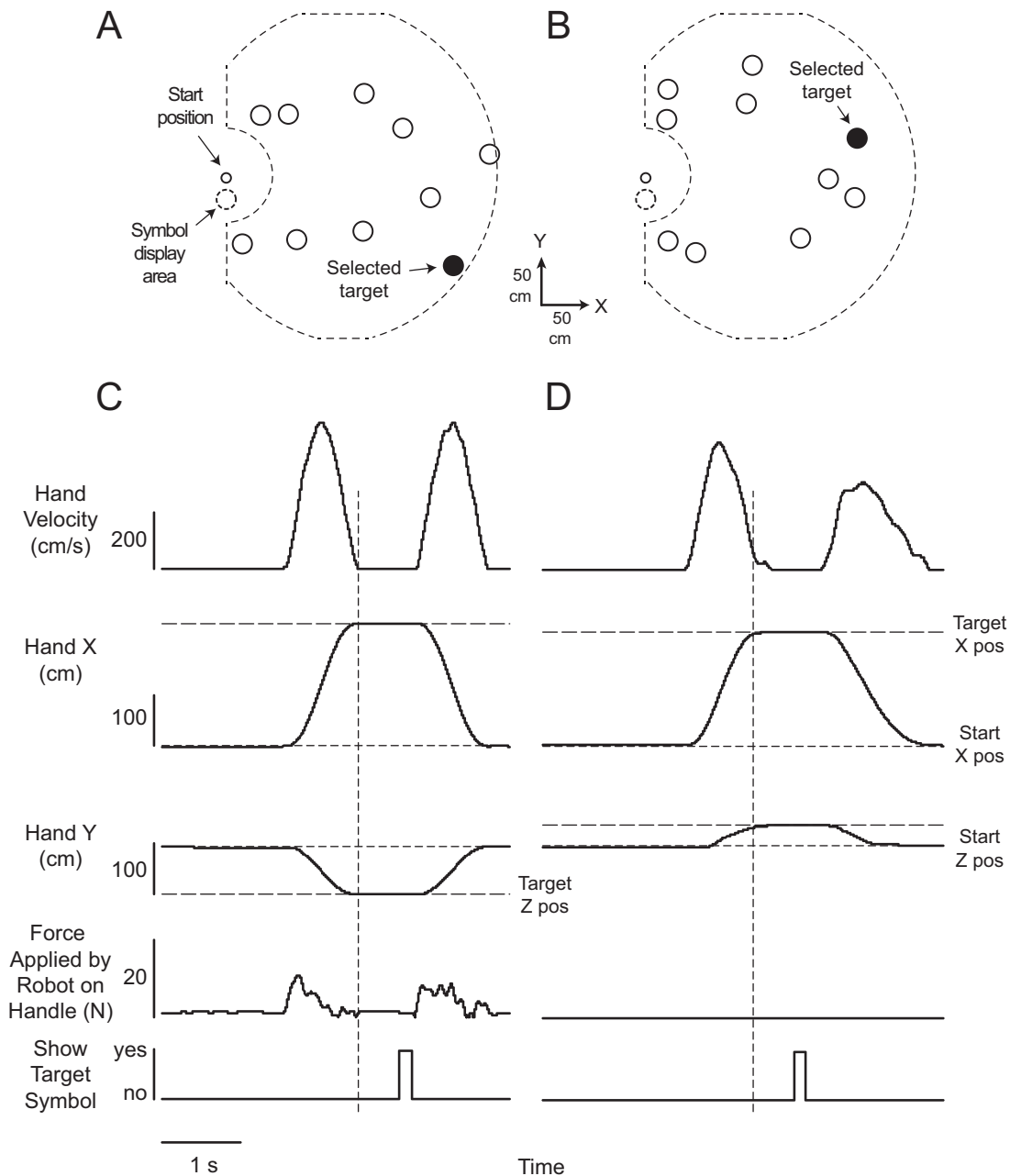
Fig. 2. (A) Target positions in a single passive training trial. (B) Target positions in a single active training trial. (C) Waveforms showing hand velocity, hand *x* and *y* positions, and force applied by the robot to the handle over time for the passive training trial shown in A. Hand velocity increased and decreased during the movement to the target and then back to the start position. The target symbol was shown after the cursor was held at that location for 500 ms. (D) Corresponding plot for the active training trial shown in B.

start position, within the area demarcated in Fig. 1B, and with a minimum distance between targets of 2.5 cm. The target circles were simultaneously visible to participants during the entire course of a block, and a unique set of target locations was used in each block. Participants completed a total of 12 experimental blocks and, for each, a subset of 10 symbols was pseudo-randomly selected from the 24 illustrated in Fig. 1C, with one symbol hidden at each target location. Each symbol was used either 6 or 7 times throughout the experiment, but never at the same location more than once. Each participant completed 6 blocks of the active condition and 6 blocks of either the passive or active-unlinked condition, in counterbalanced order. Each block consisted of 20 training trials followed by 10 test trials. Participants were explicitly instructed to remember the location of each object for a subsequent memory test.

To begin each training trial, the hand cursor was moved into the start position (actively or passively, depending on the condition). At this time, one of the 10 targets changed from white to yellow (see black targets in Fig. 2A and B) to cue the selected target. In the active condition participants initiated their own movement to this selected target. In the passive condition the robot moved the participant's hand to the target. Once the hand cursor was held within the target for 500 ms, the concealed symbol was displayed for 125 ms, and then was hidden again. The active-unlinked condition was the same as the active condition except that participants generated a movement to the left of the start position, rather than moving to the target. The symbol was displayed at the target location once participants contacted an invisible haptic (or force) wall that was generated by the robot 10 cm to the left of the start
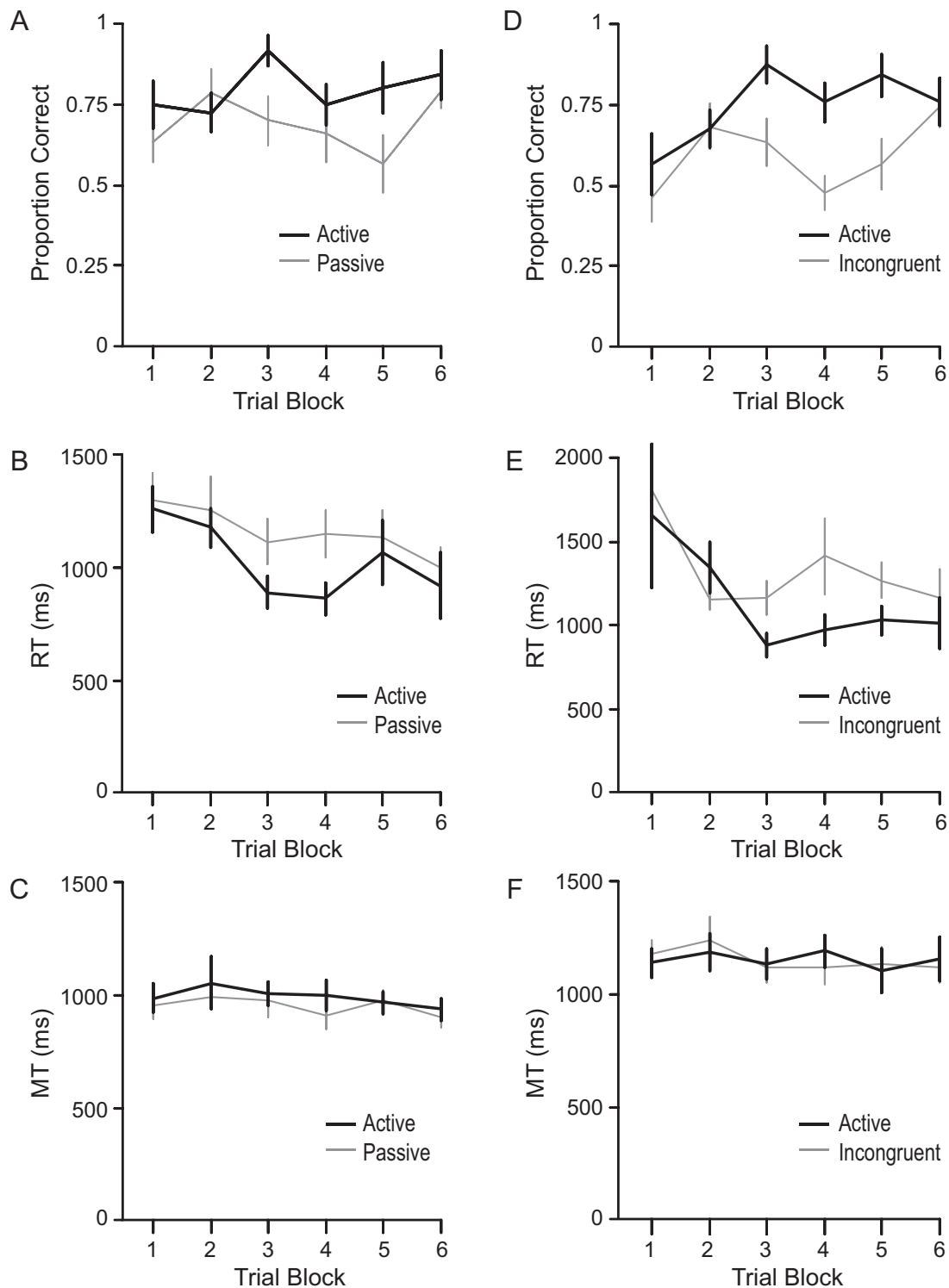
Fig. 3. (A) Proportion of correct selections for each trial block in the active and passive conditions of Experiment 1. (B) Average RT across trial blocks in the active and passive conditions. (C) Average MT across blocks in both conditions. (D) Proportion of correct selections for each trial block in the active and active-unlinked conditions of Experiment 2. (E) Average RT across trial blocks in the active and active-unlinked conditions. (F) Average MT across blocks in both conditions. In all panels, error bars represent 1 standard error.

position (Fig. 1B). For all conditions the trial was completed when the hand cursor was moved, actively or passively, back to the start position. The participant experienced each of the 10 symbol-location pairings twice in the training phase of each block. Fig. 2A and B shows the targets and selected target for a single passive and a single active training trial, respectively. Fig. 2C and D shows, for these two trials respectively, the tangential velocity of the hand,

the X and Y hand positions, the force applied by the handle to the hand, and time during which the symbol was displayed. Note that handle forces were only generated in the passive training trials.

In the subsequent test phase, after the hand cursor was actively moved to the start position one of the 10 symbols was displayed in the symbol display area (Fig. 1B), instructing the participant to move to the target they believed was hiding this symbol. The

participant made their selection by holding the cursor within the target for 500 ms. Once the selection was made, the target turned blue, but no other feedback was provided in order to avoid further learning during the test phase. Following their selection, the participant returned to the start position. This process repeated until each of the 10 symbols was shown once, in random order. The participant then experienced a 5 s feedback phase, wherein correctly selected locations appeared in green and incorrect selections in red. Note that the test phase procedures were the same for all three conditions, and required active movements to the targets on every trial.

The handle position data was used to determine if participants selected the correct object location in each trial. For each test block we calculated the proportion of correct selections. We also determined the reaction time (RT) for each trial, defined as the delay between the target symbol being displayed in the symbol display area and the participant initiating their movement to a target location. Movement initiation was deemed to have occurred when the resultant velocity of the handle exceeded 2 cm/s. In addition, we determined the movement time (MT) as the time from the initiation of movement until the hand cursor entered the selected target. To compare test phase performance between the conditions in each experiment we compared accuracy (proportion of correct responses), RT, and MT between conditions, and across blocks in separate 2 (condition) × 6 (block) repeated measures ANOVAs, with Bonferroni corrected p values for tests of simple main effects.

In Experiment 1 participants were significantly more accurate ($F_{1,11} = 11.13$, $p = .007$) in the active than passive condition (Fig. 3A). There was also a significant main effect of block ($F_{5,55} = 2.70$, $p = .030$), and a significant interaction between block and condition ($F_{5,55} = 3.30$, $p = .011$). Pairwise comparisons revealed that although accuracy was better in the active than passive condition, the largest differences were observed in blocks 3 ($p < 0.01$) and 5 ($p < 0.01$).

Participants exhibited marginally shorter ($F_{1,11} = 4.35$, $p = .061$) RTs in the active compared to passive condition (Fig. 3B). There was also a significant main effect of block ($F_{5,55} = 6.32$, $p = .003$), but no interaction between condition and block ($F_{5,55} = 6.32$, $p = .473$). RT tended to decrease across blocks, possibly due to increasing familiarity with the task. MT in the test phase did not differ between the active and passive conditions ($F_{1,11} = .74$, $p = .407$) or across blocks ($F_{5,55} = 1.97$, $p = .098$), and there was no interaction ($F_{5,55} = .30$, $p = .910$) between condition and block (Fig. 3C).

In Experiment 2 participants were more accurate ($F_{1,11} = 9.12$, $p = .012$) in the active compared to the active-unlinked condition (Fig. 3D). There was no main effect of block ($F_{5,55} = 3.27$, $p = .08$), and no interaction between block and condition ($F_{5,55} = 1.88$, $p = .22$). In terms of RT, there were no significant main effects of condition ($F_{5,55} = 1.82$, $p = .20$), or block ($F_{5,55} = 2.11$, $p = .18$), and no interaction between condition and block ($F_{5,55} = 2.14$, $p = .17$). Likewise, MT did not differ between conditions ($F_{5,55} = 0.00$, $p = .99$), or across blocks ($F_{5,55} = 0.53$, $p = .75$), and there was no interaction ($F_{5,55} = 1.94$, $p = .21$). Between-subjects comparisons revealed that there was no difference in accuracy between the active conditions of Experiments 1 and 2 ($F_{1,22} = 0.53$, $p = .47$) or between the passive condition in Experiment 1 and the active-unlinked condition of Experiment 2 ($F_{1,22} = 1.70$, $p = .21$).

Our results demonstrate that actively discovering the spatial locations of target objects conveys an advantage over passive discovery for object location memory. This finding adds to a larger literature on the advantage of active exploration for large-scale spatial memory of the environment [8,19]. Specifically, the current findings reveal a similar advantage for the representation of peripersonal, reachable space, showing that active interaction with objects in the workspace produces a stronger memory for object locations than passive interaction. Importantly, our findings also reveal that it is not simply an active movement per se that conveys an advantage, rather a self-generated movement towards

the target location provides spatial information that enriches the memory for object locations.

The active advantage for spatial memory has been attributed to efferent motor commands used to generate movements, proprioceptive information about body position, and vestibular information about head movements in space [8]. In the current study vestibular and proprioceptive differences between active and passive movements were minimized. Thus, the advantage of active over passive exploration for object location memory we observe can be attributed to differences in the motor commands produced during learning. However, it cannot be ruled out that the benefit of active learning resulted also from better proprioceptive information during active compared to passive movements [14].

The mechanism by which efferent copies of motor commands (or corollary discharge) benefit object location memory is not fully understood. A potential explanation comes from the 'event file' theory, which proposes that an event is coded as a conjunction of integrated features including object properties and the actions performed during the event [15]. Thus, in the current experiment, the motor commands during active learning are bound together with spatial locations, and perceptual properties of the hidden objects to produce an episodic memory of the event. The presentation of the visual object in the symbol display area during the test phase serves as a cue to trigger the retrieval of all of the features of the initial encounter with that object, including its spatial location. In this framework, the passive condition produces a weaker memory trace of the event because the motor commands associated with the action was not coded with the other features of the event, lowering the probability of retrieval.

An alternative, but related explanation is that self-generated actions can provide a more enriched encoding of spatial memories than passive movements. The idea that actions are incorporated into episodic memories has been around for some time [16] and it is well established that more enriched encoding allows for better episodic memory [17]. Our finding that self-generated actions are only beneficial if directed to object locations suggests that enriched memory is due to spatial information associated with the motor commands during learning. The enrichment of memory during active learning may also be partly due to increased attention relative to passive learning. Recent neuroimaging work has shown that volitional control benefits spatial learning and is linked to better engagement of a volitional control network that includes the hippocampus and prefrontal attentional networks [18].

In summary, the current data show that self-generated movements benefit object location memory more than passive movements. By using a robotic manipulandum to equate as many aspects of the arm movements between the conditions as possible, these findings corroborate previous observations that efferent motor commands play an important role in facilitating spatial learning.

References

[1] Steenhuis RE, Goodale MA. The effects of time and distance on accuracy of target-directed locomotion: does an accurate short-term memory for spatial location exist? J Motor Behav 1988;20:399–415.

[2] Harman KL, Humphrey GK, Goodale MA. Active manual control of object views facilitates visual recognition. Curr Biol 1999;9:1315–8.
[3] James KH, Humphrey GK, Vilis T, Corrie B, Baddour R, Goodale MA. Active and passive learning of three-dimensional object structure within an immersive virtual reality environment. Behav Res Methods Instrum Comput 2002;34:383–90.
[4] Held R, Hein A. Movement-produced stimulation in the development of visually guided behavior. J Comp Physiol Psychol 1963;56:872–6.
[5] Appleyard D. Styles and methods of structuring a city. Environ Behav 1970;2:100–17.
[6] Feldman A, Acredolo L. The effect of active versus passive exploration on memory for spatial location in children. Child Dev 1979;50:698–704.
[7] Chrastil ER, Warren WH. Active and passive spatial learning in human navigation: acquisition of survey knowledge. J Exp Psychol Learn Mem Cogn 2013;39:1520–37.
[8] Chrastil ER, Warren WH. Active and passive contributions to spatial learning. Psychon Bull Rev 2012;19:1–23.
[9] Gritsenko V, Krouchev NI, Kalaska JF. Afferent input, efference copy, signal noise, and biases in perception of joint angle during active versus passive elbow movements. J Neurophysiol 2007;98:1140–54.
[10] Laufer Y, Hocherman S, Dickstein R. Accuracy of reproducing hand position when using active compared with passive movement. Physiother Res Int 2001;6:65–75.
[11] Postma A, De Haan EH. What was where? Memory for object locations. Q J Exp Psychol A 1996;49:178–99.
[12] Postma A, Kessels RP, van Asselen M. How the brain remembers and forgets where things are: the neurocognition of object-location memory. Neurosci Biobehav Rev 2008;32:1339–45.
[13] Howard IS, Ingram JN, Wolpert DM. A modular planar robotic manipulandum with end-point torque control. J Neurosci Methods 2009;181:199–211.
[14] Fuentes CT, Bastian AJ. Where is your arm? Variations in proprioception across space and tasks. J Neurophysiol 2010;103:164–71.
[15] Hommel B. Event files: feature binding in and across perception and action. Trends Cogn Sci 2004;8:494–500.
[16] Engelkamp J, Zimmer HD. Memory for action events: a new field of research. Psychol Res 1989;51:153–7.
[17] Craik FIM. Levels of processing: past, present… and future? Memory 2002;10:305–18.
[18] Voss JL, Gonsalves BD, Federmeier KD, Tranel D, Cohen NJ. Hippocampal brain-network coordination during volitional exploratory behavior enhances learning. Nat Neurosci 2010;14:115–20.
[19] Brooks BM. The specificity of memory enhancement during interaction with a virtual environment. Memory 1999;7:65–78.
[20] Ruddle RA, Volkova E, Mohler B, Bülthoff HH. The effect of landmark and body-based sensory information on route knowledge. Mem Cognit 2010;39:686–99.
[21] Stackman RW. Passive transport disrupts directional path integration by rat head direction cells. J Neurophysiol 2003;90:2862–74.