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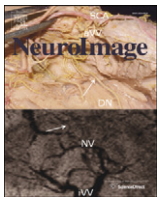

Memory for motion and spatial location is mediated by contralateral and ipsilateral motion processing cortex

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ABSTRACT

Memory and perception have been associated with common sensory cortical activity. However, previous studies have only investigated memory and perception effects associated with a single feature (i.e., spatial location or color). The aim of the present functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS) study was to assess whether memory for multiple (two) features would produce sensory cortical activity that mirrored perceptual processing of the same features. During encoding, moving or stationary abstract shapes were presented to the right or left of fixation. During retrieval, shapes were presented at fixation and participants classified each item as previously in motion or stationary within the right or left visual field. Memory for items in motion, regardless of spatial location, produced fMRI activity in perceptual motion processing region MT+. Memory for motion and spatial location produced contralateral and ipsilateral fMRI activity in perceptual motion processing sub-region MT. Following TMS to MT, memory for motion was impaired, but performance did not differ between the contralateral and ipsilateral visual fields. The present results are consistent with previous findings in that memory for motion produced fMRI activity in MT+ and was impaired following TMS to MT. However, memory for motion and spatial location produced contralateral and ipsilateral fMRI and TMS effects, deviating from the primarily contralateral perceptual processing organization of MT. The present evidence suggests that during memory for motion and spatial location only motion information is coded in motion processing cortex, while previous findings suggest spatial location information is coded in earlier extrastriate cortex.

Introduction

Retrieval has been described as a constructive process, where information processed in disparate cortical regions is combined to form a unified memory (Squire, 1992; Schacter et al., 1998). Providing support for this constructive memory framework, memory for visual items can activate visual processing cortex (Wheeler et al., 2000; Wheeler and Buckner, 2003), memory for sounds can activate auditory processing cortex (Schacter et al., 1996; Wheeler et al., 2000; Nyberg et al., 2000), and memory for odors can activate olfactory processing cortex (Gottfried et al., 2004). Feature-specific memory effects have also been observed, as memory for spatial location can activate contralateral extrastriate cortex (i.e., memory for items previously presented in the right visual field activate left extrastriate cortex and vice versa; Slotnick, 2009a; see also, Gratton et al., 1997; Fabiani et al., 2000) and memory for color can activate color processing cortex (Simmons et al., 2007; Slotnick, 2009b). The latter visual memory effects mirror the organization of visual perceptual processing, where sensory cortical regions preferentially process a specific feature (such as spatial location, color, or motion; Slotnick, 2004). Indeed, the extant evidence suggests that memory and perception are mediated by the same sensory cortical regions.

Previous studies, however, have only investigated sensory activity associated with memory for a single feature (i.e., spatial location or color). The aim of the present functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation (TMS) study was to assess whether memory for multiple (two) features (i.e., motion and spatial location) would produce sensory cortical activity that mirrored perceptual processing of the same features. During encoding, abstract shapes that were either in motion or stationary were presented to the right or left of fixation (Fig. 1, top). During retrieval, shapes were presented at fixation and participants classified each shape as previously in motion in the right visual field, previously in motion in the left visual field, previously stationary in the right visual field, or previously stationary in the left visual field (Fig. 1, bottom).

Human motion processing region MT+, which has been localized to the ascending limb of the inferior temporal sulcus (Watson et al., 1993), is comprised of sub-region MT which preferentially processes motion in the contralateral visual field (i.e., right hemisphere MT primarily processes motion in the left visual field and left hemisphere MT primarily processes motion in the right visual field) and more anterior sub-region MST which processes motion in both the contralateral visual

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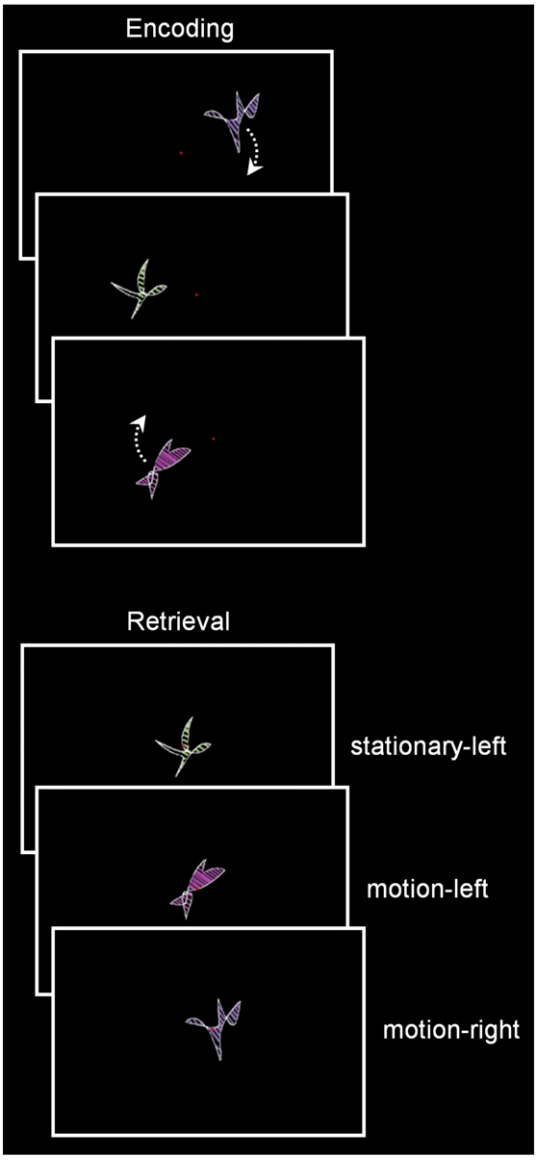

Fig. 1. Behavioral protocol. During encoding, abstract shapes were in motion (upward or downward, indicated by the curved dotted arrows) or stationary to the right or left of fixation. During retrieval, items were presented at fixation and participants classified each item as previously in motion or stationary within the right or left visual field (correct responses are shown to the right).

field and the ipsilateral visual field (Dukelow et al., 2001; Huk et al., 2002; Smith et al., 2006; Beachamp et al., 2007). Based on this perceptual processing organization, if memory effects track perception effects: 1) Memory for moving items in a given visual field should produce increased fMRI activation in contralateral motion processing sub-region MT (to a greater degree than in ipsilateral MT), and 2) TMS to MT should impair memory for motion in the contralateral visual field (to a greater degree than in the ipsilateral visual field). To anticipate the results, memory for motion produced both contralateral and ipsilateral effects, which suggests a discord between sensory cortical processing associated with visual memory and visual perception.

Materials and methods

Participants

Twelve Boston College undergraduate and graduate students took part in the study (9 females, age range 19–28 years). One participant did not complete the TMS session (female, age 20 years). Pre-screening was conducted to ensure participants were right-handed, 18–35 years old, native English speakers, and had normal or corrected-to-normal vision. Furthermore, participants were excluded if they had a history of headaches, neck pain, ringing in their ears, seizures, an immediate relative with epilepsy, metal in their body (other than fillings), brain injury, a previous electroencephalogram, a neurologic condition, potential neuropsychiatric side effects associated with medication, or might have been pregnant (exclusion criteria were adapted from Keel et al., 2000). Participants were remunerated $10 for the behavioral training session and $25/h (approximately $100) for each of the other sessions. The fMRI protocol was approved by the Massachusetts General Hospital Institutional Review Board, and other protocols were approved by the Boston College Institutional Review Board. Written and informed consent was obtained before each session commenced.

Stimuli and tasks

Participants first completed a behavioral training session which included a one-quarter length memory run and two full-length memory runs. Participants completed six memory runs in each fMRI session and two memory runs in each TMS session. Immediately before each encoding phase, an instruction screen reminded participants to always maintain fixation and remember whether each shape was moving or stationary and whether it was in the right or left visual field. During the encoding phase of each run, 24 abstract shapes spanning 4° of visual angle were presented in the right or left visual field along an arc spanning $\pm 45°$ of polar angle from the horizontal meridian with the nearest edge 2° of visual angle from fixation. Shapes were designed to avoid verbal encoding strategies (for details on shape construction, see Slotnick and Schacter, 2004). Each shape was presented for 2.5 s with an inter-trial-interval of 3.0 s. Shape sets were repeated three times during fMRI and five times during TMS (each shape set was randomized and presented sequentially). The specific number of repetitions used during TMS was selected, based on pilot results, to produce an approximately equal level of memory accuracy as during fMRI (where more repetitions during TMS counteracted the additional 10 min delay between TMS encoding and retrieval; see TMS data acquisition and analysis below). An equal number of shapes were stationary (at one of six equally spaced locations along the stimulation arc within each hemifield) or moving (smoothly traversing the entire stimulation arc within each hemifield with either upward or downward motion). In each run, all spatial locations and movement directions were presented equally often. Immediately before the retrieval phase, an instruction screen (presented for 8 s) reminded participants to always maintain fixation and displayed the previously learned response mappings. During the retrieval phase of each run, the 24 shapes from encoding were presented in random order at fixation for 3.5 s with an inter-trial-interval of 7–10 s. Participants pressed response buttons with the fingers of their left hand to classify each shape as previously in motion in the right visual field, previously in motion in the left visual field, previously stationary in the right visual field, or previously stationary in the left visual field (while the shape was on the screen). Participants also made a subsequent remember-know response to characterize their subjective experience (only remember judgments during fMRI had a sufficient number of responses to conduct a meaningful analysis). During both encoding and retrieval, no more than three shapes of a given type were presented sequentially. Shapes were never repeated across runs. Sets of shapes (motion-right, motion-left, stationary-right, stationary-left) were counterbalanced across participants using a Latin Square design. Memory related activity was identified by contrasting accurate retrieval (old-hits) with inaccurate retrieval (old-misses; Slotnick and Schacter, 2004, 2010; Wheeler and Buckner, 2004).

Each participant also completed one motion processing localizer run which consisted of a full-field stimulus (14.2×18.9° of visual angle) that alternated between periods of moving dots and stationary dots (for additional details, see Slotnick and Yantis, 2005; Thakral and Slotnick, 2009). The stimulus consisted of 400 dots (0.05° of visual angle in diameter) that appeared along the outer edge at random locations and then moved toward central fixation with 100% coherence at 5°/s. Each of 8 moving-stationary cycles lasted 28 s. Participants were instructed to maintain central fixation and, to encourage vigilance, press a button when they detected a brief slowdown of all the dots (which occurred twice per motion period).

fMRI data acquisition and analysis

MRI was conducted using a Siemens 3 Tesla Trio Scanner with a standard head coil (Siemens Industry Inc., Erlangen, Germany). Functional images were acquired using an echo planar imaging sequence (TR = 2000 ms, TE = 20 ms, flip angle = 90°, field-of-view = 256×256 mm^2, acquisition matrix = 64×64, slices = 33, slice thickness = 4 mm, 4 mm isotropic resolution). Anatomic images were acquired using a magnetization prepared rapid gradient echo sequence (TR = 30 ms, TE = 3.3 ms, flip angle = 40°, field-of-view = 256×256 mm^2, acquisition matrix = 256×256, slices = 128, slice thickness = 1.33 mm, 1.33×1×1 mm resolution). Analysis was conducted using BrainVoyager QX (Brain Innovation B.V., Maastricht, The Netherlands) in volume space and then projected onto cortical surface representations. Pre-processing of functional data included slice-time correction, motion correction, and temporal filtering by removal of linear trends and components at or below 2 or 3 cycles per run length for memory data or motion localizer data, respectively (using a general linear model to remove low frequency Fourier basis sets). Spatial smoothing was not conducted for memory data (to maximize spatial resolution), but motion localizer pre-processing included convolution with a 4 mm smoothing kernel. Functional and anatomic images were transformed into Talairach space for the memory analysis, but were not transformed for the motion localizer analysis which was used for TMS neuronavigation (and thus was necessarily conducted in native/non-distorted space).

A random-effect general linear model was used to conduct the memory analysis. For each participant, a canonical hemodynamic response function was convolved with the protocol of each event (i.e., a square wave defined by each event onset and the subsequent behavioral response) to produce the corresponding hemodynamic response model. Events included encoding of shape type (in motion or stationary) and location (right visual field or left visual field), accurate retrieval of shape type and location, accurate retrieval of shape type and inaccurate retrieval of location, inaccurate retrieval of shape type and accurate retrieval of location, inaccurate retrieval of shape and location, failures to respond, and a constant. Encoding trials and no response trials were assumed to have a duration of 2.5 and 3.5 s, respectively. The cortical regions that were associated with motion at encoding, regardless of spatial location, were identified using the contrast shapes in motion>stationary shapes. The threshold was adjusted (to $t = 12.50$, $p < 1\times10^{-35}$) such that this activity was restricted to the ascending limb of the inferior temporal sulcus, the anatomic location of perceptual motion processing region MT+ (Watson et al., 1993; Dukelow et al., 2001; Huk et al., 2002; Smith et al., 2006; Beachamp et al., 2007). That is, both functional and anatomic criteria were used to identify the location of motion processing region MT+. In an effort to balance type I and type II error, an individual voxel threshold of $p < 0.01$ was enforced for all other contrasts (including each encoding and retrieval contrast that was entered into a conjunction, used to isolate retrieval related reactivation of the same cortical regions associated with encoding/perception). Critically, all results were false discovery rate corrected for multiple comparisons to $p < 0.05$, and a minimum cluster extent of at least 3 resampled voxels (at least 1 original voxel) was also enforced. One-tailed paired *t*-tests were used based on previous findings that motion perception increases activity in motion processing cortex (O'Craven et al., 1997; Slotnick and Yantis, 2005; Thakral and Slotnick, 2009).

To guide TMS neuronavigation (which is detailed below) on an individual participant basis, motion processing sub-region MT was identified in each hemisphere by contrasting periods of moving dots>stationary dots (O'Craven et al., 1997; Slotnick and Yantis, 2005; Thakral and Slotnick, 2009). This activity was then projected onto each participant's cortical surface representation (see Slotnick, 2005, for detailed cortical segmentation and reconstruction procedures). The precise location of motion processing sub-region MT was identified using three constraints: 1) MT was on the posterior bank of the ascending limb of the inferior temporal sulcus (Huk et al., 2002; Beachamp et al., 2007; Kolster et al., 2010), 2) MT was associated with significant motion related activity, and 3) MT was within the range of motion processing cortex coordinates produced by a meta-analysis of the literature (Slotnick et al., 2005). These constraints yielded the specific location of MT that was subsequently used as a target during TMS.

TMS data acquisition and analysis

The BrainVoyager TMS Neuronavigation System was used to target motion processing sub-region MT in each hemisphere (see Sack et al., 2006; McKeefry et al., 2008). Landmarks on the head and TMS coil were identified in external space (using a digitizer pen), identified in BrainVoyager, and then co-registered. Six ultrasound transmitters, three on the head and three on the TMS coil, emitted signals that were picked up by a receiving sensor device to track the location of the TMS coil in real-time relative to the head (and the linked cortical surface). Before TMS commenced in a given hemisphere, the target location (MT) was marked on the cortical surface (Fig. 2). To temporarily disrupt MT during retrieval, a Magstim Rapid^2 system with a Double 70 mm Coil (The Magstim Company Ltd., Carmarthenshire, Wales) was used to apply 1-Hz repetitive TMS to MT at 70% of maximum output for 10 min between the encoding phase and the retrieval phase. The coil was positioned approximately perpendicular to the

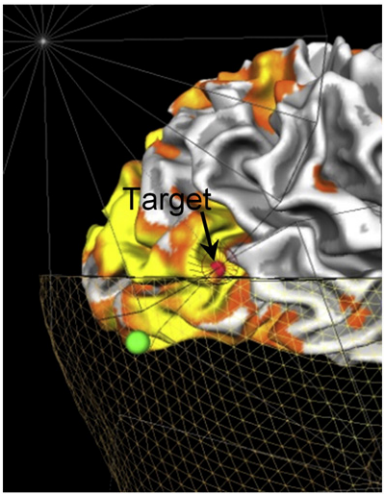

Fig. 2. fMRI guided neuronavigation. A representative participant's posterior head surface (shown in brown wireframe) and posterior right hemisphere cortical surface with motion related activity (more significant activity is shown in yellow). The TMS coil, which is only partially visible, is delineated by two wireframe wheels. TMS was used to target motion processing sub-region MT, the red sphere on the posterior bank of the ascending limb of the inferior temporal sulcus demarcated by the black arrow and text (the green sphere represents a TMS coil landmark).

head surface with slight adjustment to ensure the TMS beam was focused on MT, on the posterior bank of the inferior temporal sulcus. Stimulation of the anterior bank of the inferior temporal sulcus, the anatomic location of motion processing sub-region MST (Huk et al., 2002; Beachamp et al., 2007), was specifically avoided. The TMS cable was oriented downward 45° from horizontal in the posterior direction. During TMS, participants made odd/even judgments to random numbers presented in the center of the screen. The initial hemisphere of TMS was randomly selected, with the constraint that each hemisphere (left and right) was targeted first equally often across participants. Behavioral testing was completed within 5 min of TMS offset. There was a 30 min rest period following TMS to the first hemisphere and a 15 min rest period following TMS to the second hemisphere (to ensure TMS effects had completely dissipated before the session concluded; Kosslyn et al., 1999). Of importance, memory accuracy for previously moving items and stationary items did not depend on the temporal order of the TMS runs (both $ts<1$), which indicates that TMS effects were restricted to the subsequent retrieval phase (i.e., encoding in the second TMS run was not impaired following the first TMS run).

It is notable that 'no TMS' was the only baseline condition in the present study. While this baseline measure of performance has been used previously (Kosslyn et al., 1999; McKeefry et al., 2008; Gagnon et al., 2010), it is common to stimulate a different region that can be assumed not to participate in the function of interest (e.g., the vertex; Brascamp et al., 2010; Innocenti et al., 2010; Machizawa et al., 2010). Of relevance, memory for previously stationary items in the present study can be considered a baseline event type, as TMS to motion processing sub-region MT should not impair processing of non-motion features (Walsh et al., 1998; Ellison et al., 2007). Thus, in the present study, baseline performance was measured with the baseline condition (no TMS) as well as the baseline event type (stationary items).

It should be underscored that the fMRI and TMS protocols differed in both the number of runs, the delay between runs, and the delay between the encoding and retrieval phases within each run (where only TMS had between and within run delays); however, memory accuracy for stationary items, the baseline event type, was not significantly different in the no TMS and TMS conditions (see Results, Fig. 4A) suggesting these protocol manipulations did not produce substantial differences in general memory performance. Moreover, event related analysis was conducted such that the specific event-types of interest were the same for both the fMRI and TMS analysis.

When computing memory performance, the no TMS (control) condition included behavioral data from the fMRI session and an event-related potential session (the event-related potential results were not considered in the present manuscript). One-tailed *t*-tests were used to assess TMS induced memory effects, based on previous findings that TMS to motion processing cortex impairs perception of motion (Sack et al., 2006; McKeefry et al., 2008; see also, Moo et al., 2008). The analysis was restricted to hit rates as each miss/false alarm rate was equivalent to 1 hit rate (such that analysis of TMS induced hit rate decreases or miss rate increases produced the identical results).

Eye movements

To ensure participants were able to maintain fixation, nine participants (who had taken part in the fMRI and TMS sessions) completed a memory run while eye movements were monitored with an iView Hi-Speed 500 Hz monocular eye tracking system (Senso-Motoric Instruments Inc., Boston, MA, USA). All participants maintained fixation to within 1° of the central fixation cross during both encoding and retrieval. Of additional relevance, contralateral perception effects were also observed during fMRI at encoding (see fMRI results; Fig. 3B) which further confirmed that participants maintained fixation (if participants had looked at the stimuli during encoding the items would have been processed at fixation/in the central visual field and contralateral effects would not have been observed).

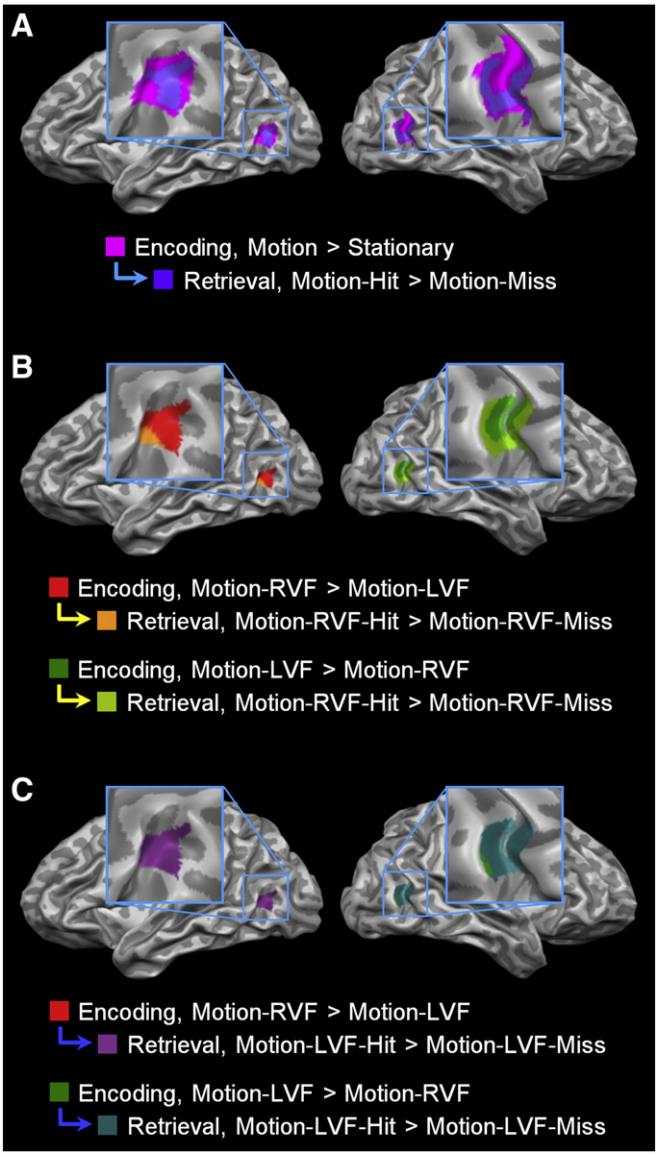

Fig. 3. fMRI results. A. Encoding of items in motion versus encoding of stationary items (encoding, motion>stationary) produced activity in motion processing region MT+ within the ascending limb of the inferior temporal sulcus (left and right hemisphere lateral surface representations are shown, with gyri and sulci in light gray and dark gray, respectively). Retrieval of motion (retrieval, motion-hit>motion-miss) produced bilateral activity within MT+ (see color keys for all contrasts). B. Within MT+, encoding of items in motion within the right visual field versus encoding of items in motion within the left visual field (encoding, motion-RVF>motion-LVF) produced activity that was isolated to the contralateral/left hemisphere, and the opposite contrast (encoding, motion-LVF>motion-RVF) produced activity that was isolated to the contralateral/right hemisphere. Retrieval of motion in the right visual field (retrieval, motion-RVF-hit>motion-RVF-miss) produced activity in both left and right hemisphere encoding regions. C. Retrieval of motion in the left visual field (retrieval, motion-LVF-hit>motion-LVF-miss) also produced activity in both left and right hemisphere encoding regions.

Results

fMRI results

Encoding/perception of motion (encoding, motion>stationary) produced activity in both left and right hemisphere motion processing region MT+, on the posterior bank and the anterior bank of the

ascending limb of the inferior temporal suclus (corresponding to motion processing sub-region MT and sub-region MST, respectively; Dukelow et al., 2001; Huk et al., 2002; Beachamp et al., 2007). Memory for items previously in motion (retrieval, motion-hit>motion-miss) reactivated the same regions (Fig. 3A; retrieval of motion also activated MT+, identified by the motion perception localizer; Supplementary Fig. 1). By comparison, memory for previously stationary items (retrieval, stationary-hit>stationary-miss) did not produce any activity in motion processing region MT+.

Of direct relevance to the present aim, an analysis was conducted to determine whether memory for motion in a given hemifield preferentially activated contralateral motion processing sub-region MT, as is known to occur during motion perception and attention (Dukelow et al., 2001; Huk et al., 2002; Slotnick and Yantis, 2005). As expected, encoding/perception of motion in the right versus left visual field (encoding, right visual field motion>left visual field motion) produced activity that was restricted to left hemisphere MT and encoding/perception of motion in the left versus right visual field (encoding, left visual field motion>right visual field motion) produced activity that was restricted to right hemisphere MT (Fig. 3B, C). Of importance, activity was largely restricted to the posterior bank of the inferior temporal sulcus, the anatomic location of sub-region MT (compare Fig. 3B to A). There was no evidence of preferential contralateral memory effects, as memory for motion in the right visual field (retrieval, motion-right visual field-hit>motion-right visual field-miss) produced activity within both left and right hemisphere MT rather than being restricted to the contralateral hemisphere (Fig. 3B). Memory for motion in the left visual field (retrieval, motion-left visual field-hit>motion-left visual field-miss) also produced activity in both left and right hemisphere MT (Fig. 3C). In an effort to uncover contralateral memory effects, accurate memory for motion in the right visual field was compared to accurate memory for motion in the left visual field (retrieval, motion-right visual field-hit>motion-left visual field-hit) and vice versa, to subtract out non-lateralized activity (Slotnick, 2009a, 2010), but no preferential contralateral memory effects were observed.

In further characterization of the preceding effects, accurate memory for motion was found to be most highly associated with remember responses (as opposed to know responses). Specifically, motion-hits were associated with remembering 79.8 ± 4.2% of the time. As such, the preceding analyses were conducted using motion-hit-remember responses with the same baseline measures, and the identical pattern of results was observed. This suggests that the preceding memory effects in motion processing cortex reflect the subjective experience of motion.

TMS results

TMS to motion processing sub-region MT produced a memory impairment for items in motion, regardless of the hemisphere of stimulation or item spatial location. As shown in Fig. 4A, memory accuracy for items previously in motion (motion-hit rate) was significantly lower following TMS to motion processing sub-region MT as compared to no TMS ($t = 1.85$, $p < 0.05$), while memory accuracy for previously stationary items (stationary-hit rate) did not differ following TMS to MT as compared to no TMS ($t < 1$; the item type × stimulation condition interaction was significant, $F = 4.98$, $p < 0.05$). Moreover, following TMS to MT, memory accuracy for items previously in motion was no better than chance ($t = 1.22$, $p = 0.13$; chance = 0.50), while accuracy was significantly greater than chance for all the other conditions (all $ps < 0.01$). These results suggest that TMS to motion processing sub-region MT in either hemisphere largely if not completely eliminated memory for motion (but had no measurable effect on memory for stationary items).

There was no evidence of preferential contralateral memory effects following TMS to MT for items previously in motion

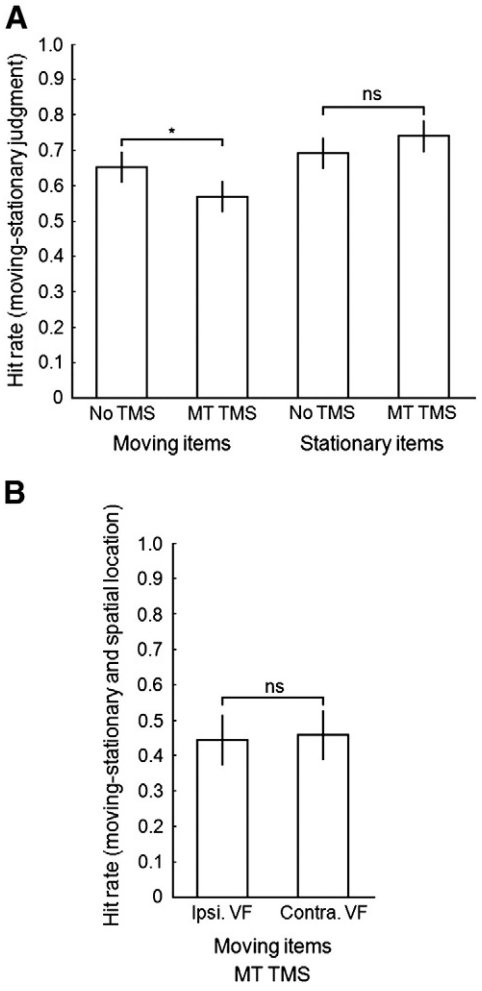

Fig. 4. TMS results. A. Moving-stationary memory accuracy associated with items previously in motion (motion-hit rate) and stationary items (stationary-hit rate), with no TMS (control condition) or following TMS to motion processing sub-region MT. B. Following TMS to MT, moving-stationary and spatial location memory accuracy associated with items previously in motion (motion-hit and spatial location-hit rate) in the ipsilateral (ipsi.) visual field (VF) and the contralateral (contra.) visual field.

(Fig. 4B). Memory accuracy for items previously in motion in the contralateral visual field (motion-hit and spatial location-hit rate) did not differ from memory accuracy for items in the ipsilateral visual field ($t < 1$; the item type × visual field interaction was also not significant, $F = 1.30$, $p = 0.28$; Supplementary Fig. 2A). In an effort to uncover contralateral motion effects, the preceding analysis was conducted without regard to spatial location accuracy, but a similar pattern of results was obtained (Supplementary Fig. 2B).

Discussion

The present fMRI results showed that memory for motion can reactivate motion processing region MT+, and the TMS results showed motion processing sub-region MT is necessary for remembering motion. These results complement and extend previous work indicating memory can reactivate perceptual processing regions, where memory for spatial location has been shown to activate contralateral extrastriate cortex (Slotnick, 2009a) and memory for color has been shown to activate color processing cortex (Simmons et al., 2007; Slotnick, 2009b). Taken in isolation, these findings would suggest that perception and memory are associated with common neural substrates.

A more detailed picture emerged when memory effects and perception effects for two features were compared. Contrary to the

preferentially contralateral organization of motion processing sub-region MT during perception and attention (Dukelow et al., 2001; Huk et al., 2002; Smith et al., 2006; Slotnick and Yantis, 2005), we found no evidence that accurate memory for motion produced contralateral greater than ipsilateral effects in MT. Rather, memory for motion in either hemifield produced bilateral (contralateral and ipsilateral) fMRI activity in motion processing sub-region MT, and TMS to MT impaired memory for motion in both the contralateral visual field and the ipsilateral visual field. While a null finding should always be treated with caution, lateralized TMS memory effects were observed for stationary items (Supplementary Fig. 2A) which argues against the possibility that our procedures had generally poor sensitivity.

The present findings suggest that during accurate memory for motion and spatial location only the motion information is coded in motion processing cortex, as opposed to perception where both motion and spatial location is coded in this region. Of relevance to this point, memory accuracy for spatial location without regard to moving-stationary accuracy (spatial location-hit rate) did not differ for items in motion following TMS to MT (0.7174 ± 0.0419) as compared to no TMS (0.7216 ± 0.0419, $t<1$), nor did memory accuracy for spatial location differ for stationary items following TMS to MT (0.7303 ± 0.0417) as compared to no TMS (0.7161 ± 0.0417, $t<1$), and memory accuracy for spatial location following TMS to MT also did not differ between items in motion and stationary items ($t<1$). That is, spatial location accuracy for both types of stimuli was unimpaired following TMS to MT, further supporting the conjecture that spatial location information is not coded in sub-region MT during retrieval. In a recent study, we found that memory for spatial location preferentially activated contralateral extrastriate cortex (BA18; Slotnick, 2009a). This finding, in conjunction with the present results, suggests that during memory for motion and spatial location, motion information may be coded in motion processing cortex and spatial information may be separately coded in extrastriate region BA18.

An alternative explanation for the present non-lateralized memory effects is that participants engaged in a retrieval strategy that did not involve visualization of stimuli in the previously presented peripheral location. For instance, stimuli may have been encoded using a verbal motion-stationary association strategy, but retrieval of verbal information would not be expected to produce the robust visual memory effects observed. Stimuli may have also been visualized during retrieval as moving in the central visual field, which might have produced the contralateral and ipsilateral memory effects observed. However, in a previous study we employed a similar spatial location memory protocol (without memory for motion) and observed contralateral memory effects in extrastriate cortex (BA18; Slotnick, 2009a). As the spatial retrieval component was similar in this previous study and in the present study, it follows that the lack of contralateral memory effects in the present study likely reflects the non-lateralized nature of retrieval related activity in MT.

While we aimed to selectively impair processing in sub-region MT using TMS, it is possible that processing in adjacent sub-region MST was also impaired due to the close anatomic proximity or functional interactions between these sub-regions. Along the same lines, TMS induced effects in more distant cortical regions may have influenced the present results (Speer et al., 2003a, b; Okabe et al., 2003; Rounis et al., 2005; Knoch et al., 2006; Rowe et al., 2006; Hanaoka et al., 2007; for a review see Lee et al., 2006). As sub-region MST processes motion in both visual fields, TMS induced disruption of processing in this region could explain the observed memory impairments in the contralateral and ipsilateral visual fields. However, in a recent motion perception TMS study, we employed the identical procedures as in the present study to target sub-region MT and observed a significantly greater impairment in contralateral versus ipsilateral motion perception (Thakral and Slotnick, in press). As MT preferentially processes motion in the contralateral visual field while MST processes motion in both the contralateral and ipsilateral visual fields (Dukelow et al., 2001; Huk et al., 2002; Smith et al., 2006; Beachamp et al., 2007), this finding suggests that MT was selectively targeted in the present TMS study. Moreover, we observed bilateral fMRI retrieval effects on the posterior bank of the ascending limb of the inferior temporal sulcus, the locus of sub-region MT (Huk et al., 2002; Beachamp et al., 2007; Kolster et al., 2010), and the same pattern of non-lateralized retrieval effects was observed with TMS. This convergent evidence, based on two independent techniques, suggests the present non-lateralized TMS findings were not simply due to effects in motion processing sub-region MST or a more distant cortical region. It is also unclear how TMS effects in distant cortical regions that are not associated with motion processing could produce the present motion specific memory impairments. Still, we cannot rule out the possibility that regions other than MT may have been modulated by TMS in the current study. Critically, even if the present non-lateralized TMS results were due to stimulation of both MT and MST, the present TMS findings are the first to show that motion processing region MT+ is necessary for accurate retrieval of motion information.

The present findings can also be compared with previous modality-specific evidence, where a subset of the same regions associated with visual or auditory encoding/perception have been shown to reactivate during visual or auditory retrieval (Wheeler et al., 2000; Nyberg et al., 2000). It is notable that encoding of stimuli associated with a given modality (such as objects or sounds) produces activity that spans a large area of cortex (e.g., during object encoding, activity spans ventral occipital-temporal cortex, BA18/19, and extends into parietal cortex, BA19/7; Wheeler et al., 2000). The level of detail at which inferences can be made is necessarily limited by the spatial extent of cortical activity associated with encoding/perception. By comparison, when retrieval of an individual feature reactivates the same spatially restricted region of cortex associated with encoding/perception of that feature, the findings arguably provide more compelling evidence that encoding and retrieval are both mediated by this region. Of particular relevance, when encoding and retrieval effects dissociate, as in the present study, an analysis at the feature-specific level allows for readily interpretable results. Such differential effects would likely be washed out if the analysis was conducted at the modality-specific level (which involves collapsing over many individual features). Still, the modality-specific evidence is consistent, to some degree, with the present and previous feature-specific results, and suggests that retrieval involves the recapitulation of encoding/perceptual processing. Moreover, the present TMS findings provide the first evidence, to our knowledge, that feature-specific activity is necessary for accurate remembering, rather than reflecting an associated cognitive process such as post-retrieval imagery (Slotnick et al., 2005).

While it has commonly been assumed that memory effects mirror perceptual effects (Buckner and Wheeler, 2001; Thompson-Schill, 2003; Slotnick, 2004; Martin, 2007), the present results suggest that the sensory cortical processes underlying memory and perception can have key differences. Specifically, the present results indicate that during memory for motion and spatial location only motion information is processed in motion processing cortex, while previous results indicate that during perception of motion and spatial location both motion and location information is processed in motion processing cortex. Future studies may benefit from employing tasks that require memory for multiple specific features. In this way, the common and differential neural substrates associated with memory and perception can be systematically investigated.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.neuroimage.2010.11.077.

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