

Re-examining overlap between tactile and visual motion responses within hMT+ and STS

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ABSTRACT

Here, we examine overlap between tactile and visual motion BOLD responses within the human MT+ complex. Although several studies have reported tactile responses overlapping with hMT+, many used group average analyses, leaving it unclear whether these responses were restricted to subregions of hMT+. Moreover, previous studies either employed a tactile task or passive stimulation, leaving it unclear whether or not tactile responses in hMT+ are simply the consequence of visual imagery. Here, we carried out a replication of one of the classic papers finding tactile responses in hMT+. We mapped MT and MST in individual subjects using visual field localizers. We then examined responses to tactile motion on the arm, either presented passively or in the presence of a visual task performed at fixation designed to minimize visualization of the concurrent tactile stimulation. To our surprise, without a visual task, we found only weak tactile motion responses in MT (6% of voxels showing tactile responses) and MST (2% of voxels). With an unrelated visual task designed to withdraw attention from the tactile modality, responses in MST were reduced to almost nothing (<1% regions). Consistent with previous results, we did observe tactile responses in STS regions superior and anterior to hMT+. Despite the lack of individual overlap, group-averaged responses produced strong spurious overlap between tactile and visual motion responses within hMT+ that resembled those observed in previous studies. The weak nature of tactile responses in hMT+ (and their abolition by withdrawal of attention) suggests that hMT+ may not serve as a supramodal motion processing module.

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Introduction

Although human motion-sensitive middle temporal cortex (hMT+ complex) is traditionally thought of as visual cortex, in recent years, the human neuroimaging literature has presented several studies suggesting tactile responses (Hagen et al., 2002; Blake et al., 2004; Beauchamp et al., 2007; Ricciardi et al., 2007; Summers et al., 2009; Matteau et al., 2010; Sani et al., 2010) selective for the direction of tactile motion (van Kemenade et al., 2014) in hMT+ within sighted subjects, as well as disruption of tactile processing with rTMS inhibition over the expected site of hMT+ (Ricciardi et al., 2011), even for passive tactile stimulation. This has led to the suggestion that regions within hMT+ may be supramodal, processing motion regardless of the sensory modality in which it is presented (Pascual-Leone and Hamilton, 2001; Ricciardi et al., 2014).

Here, we carried out a replication of one of the most influential papers showing tactile responses with hMT+, that of Hagen et al.

(2002). This paper is often cited as evidence that in most normally sighted individuals, hMT+ responds to passive tactile stimulation. Within this replication, we were particularly interested in examining three aspects of these tactile responses: (1) the extent of overlap between tactile responses and individually localized hMT+, (2) the location of responses within hMT+ with respect to MT, and (3) in an extension of the original design, we examined whether responses to tactile stimulation near hMT+ would survive withdrawal of attention.

We were interested in examining how clearly tactile motion responses overlapped with hMT+ because many (though not all, see Discussion) of the studies cited above relied on stereotactic coordinates (Matteau et al., 2010; Wacker et al., 2011), or group-averaged data localizers (Ricciardi et al., 2007; Summers et al., 2009; Sani et al., 2010) to identify the location of hMT+. However, the expected location of hMT+ varies widely across individuals (Watson et al., 1993; Dumoulin et al., 2000; Huk et al., 2002). Thus, in some studies, tactile motion responses from either MST (Beauchamp et al., 2007), satellite regions of hMT+, or nearby polysensory areas (Beauchamp et al., 2008) might easily have contributed to group-averaged responses attributed to the MT proper.

We were interested in the location of tactile responses with respect to subregions of the hMT+ complex and the superior temporal sulcus

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because the temporal cortex contains a number of regions sensitive to visual motion including MT, ventral and dorsal MST, and more anteriorly, regions in the lower superior (LST) and the fundus of the superior temporal (FST) sulcus. These motion areas are thought to differ in their patterns of functional selectivity and role. A large amount of literature suggests that neurons in MT are restricted to the contralateral visual field and respond to relatively simple as well as more complex motions. In contrast, neurons in MST tend to represent more complex optic flow patterns, and respond to ipsilateral as well as contralateral stimuli. There are also a number of more anterior regions that respond to object-centered (FST/LST) and action-related (FST/LST/STPm) motions (Tanaka et al., 1993; Nelissen et al., 2006). These areas, like MST, respond to ipsilateral as well as contralateral stimulation (Tanaka et al., 1986). By using a visual motion stimulus that contained translational moving dots 10° from fixation either in the left or right visual field (based on Huk et al., 2002) our goal was to isolate MT from other regions of the hMT+ complex, and thereby examine whether tactile motion responses would be found in MT itself.

Finally, we were interested in whether tactile responses in hMT+ or the superior temporal sulcus would survive the withdrawal of visual attention from the tactile stimulus. There is now a converging body of literature showing that implicit motion within non-moving stimuli such as static pictures of moving objects (David and Senior, 2000; Kourtzi and Kanwisher, 2000; Senior et al., 2000) or sentences about moving stimuli (Saygin et al., 2010) are sufficient to elicit BOLD responses in hMT+. Given these findings, it seems plausible that tactile responses within hMT+ elicited by tactile stimuli might similarly be the result of 'implicit' motion rather than directly being driven by tactile stimulation. To examine this, we compared tactile motion responses in hMT+ and the superior temporal sulcus when subjects were either blindfolded, or carried out an attentionally demanding fixation task that consisted of a modified version of the memory game 'Simon©'.

The Hagen et al. study used 9 subjects and found tactile responses within hMT+ in the majority of subjects. Because our goal was to very accurately localize hMT+ within each individual, we modified the Hagen et al. design slightly and chose a protocol that focused on a small number of individuals (5) with high experimental power within each individual. We therefore collected out four sessions of data (2 sessions identifying the location of hMT+/MT/MST, and 2 sessions collecting tactile responses) on 5 individuals.

Methods

Participants

Participants were 5 young, right-handed individuals with normal vision (3 males; 27 ± 3.2 years old). All participants reported normal hearing and no history of psychiatric illness. Written and informed consent was obtained from all participants prior to the experiment, following procedures approved by the University of Washington.

MRI scanning

Scanning was performed at the DISC Center at the University of Washington with a 3 T Philips Achieva system equipped with a 32-channel SENSE head coil. Three-dimensional (3D) anatomical images were acquired at 1 × 1 × 1 mm resolution using a T1-weighted MPRAGE (magnetization-prepared rapid gradient echo) sequence. Blood oxygenation-level dependent (BOLD) functional scans were acquired with the following common parameters: 2.75 × 2.75 × 3 mm voxels; flip angle = 76°; field of view = 220 × 220. A continuous block design was used for all functional scans: a repetition time (TR) of 2 s was used to acquire 30 transverse slices (TE 30 ms).

Tactile stimulation

Tactile motion, no visual task. Following Hagen et al. (2002), we used a tactile motion stimulus consisting of a brush stroked proximal-to-distal along the right or the left volar forearm (Fig. 1A). A goat hair oval mop brush (3/4 in.) was manually applied with a velocity of 6–8 cm/s over 30–40 cm of skin. Each stroke took about 5 s, with successive strokes separated by a delay of 1 s. Participants were blindfolded and were instructed to pay attention to the brush. Each tactile block lasted 24 s, during which a total of four strokes were applied. Tactile blocks were separated by a 12 s resting block, during which participants were presented with no strokes. Through headphones, the experimenter received beep instructions indicating the beginning and ending of stroking and resting periods. Right and left arms were stimulated in separate scans. Every participant performed four scans, two for each arm. Each scan lasted 6 min, and included 10 24-s tactile blocks and 10 12-s resting blocks.

Tactile motion, with visual task. This condition was identical to that described above except that subjects were instructed to perform a visual task at fixation with their unstimulated hand (Fig. 1B). We used a modified version of the memory game 'Simon©'. This task was designed to not contain motion, and to be temporally uncorrelated with the tactile task. Four quadrants of a 0.5° circle were defined by the four arms of the fixation cross. We only used the two quadrants on the right side of the circle and two corresponding colors (upper quadrant red, lower quadrant green). Subjects memorized a sequence of color flashes in which each color was flashed for 0.25 s with an interval of 0.33 s in between colors. Subjects then reproduced it with a 2-key response box, with each response button corresponding to one quadrant/color. If subjects correctly reproduced the sequence, the number of flashes in the sequence increased by 1 after a pause of 0.25 s. If subjects made a mistake in reproducing the sequence, the last shown color was flashed four times for a total duration of 1 s. Then the sequence length was reset to 1. Subjects played the game at their own pace throughout each scan with their unstimulated hand so no aspect of the Simon game (either the timing of the presentation of the flashes or the timing of subjects' responses) was systematically related to the timing of tactile stimulation.

Every participant performed four scans, two for each arm. Each scan lasted 6 min, and included 10 24-s tactile blocks and 10 12-s resting blocks.

Visual stimulation conditions

All visual stimuli were generated using MATLAB and PsychToolbox (Brainard, 1997; Pelli, 1997). Visual stimuli were back-projected onto a screen mounted in the bore of the magnet and viewed through a mirror attached to the MR head coil. The display area covered ~27 × 22° at a viewing distance of 68 cm.

For all the conditions described below, dots were white on a black background. To prevent the tracking of individual dots, dots had a limited lifetime (200 ms). In the moving condition, all the dots moved coherently in one of 8 directions (spaced evenly between 0° and 360°) with a speed of 8° per second. The direction of motion changed once per second (the same direction was prevented from appearing twice in a row). In static conditions, dots were presented without motion, and the positions of the dots were reset once per second. In fixation conditions, participants were presented with only the fixation cross but no dots.

Full-field hMT+ visual motion localizer. The hMT+ visual motion localizer stimulus (Fig. 1C) consisted of blocks of moving, static, and a fixation condition containing no dots. Dots were presented within a circular aperture (radius 8°) with a central fixation cross surrounded by a gap (radius 1.5°, to minimize motion-induced eye-movements) in the dot field. Each dot subtended 0.3° (dot density 1 per degree). Participants were asked to fixate throughout the scan and performed no task. Each block lasted 10 s, during which one of the three visual

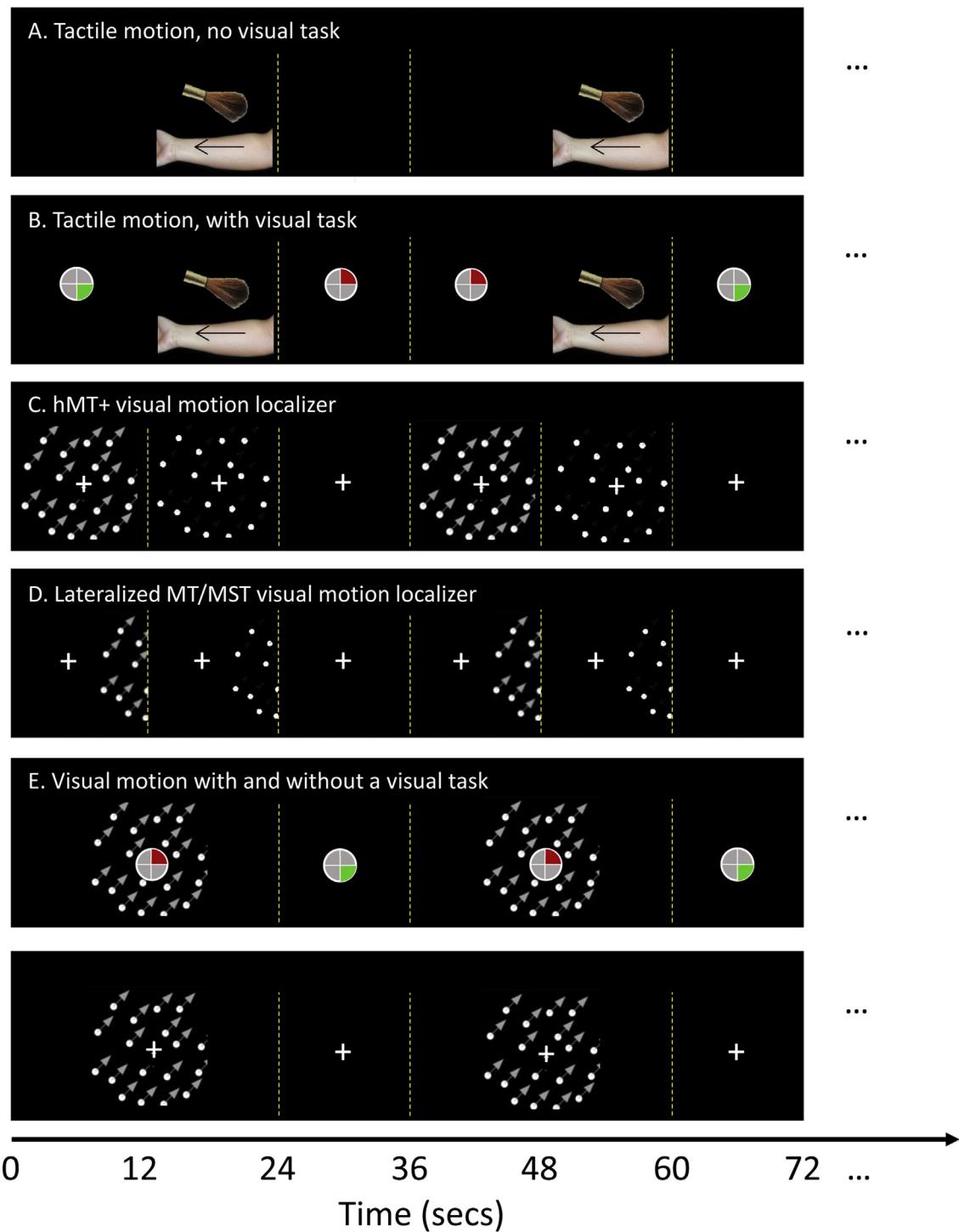


Fig. 1. Schematic of the tactile and visual paradigm for the following conditions: (A) Tactile stimulation without a visual task. Left and right arms were stimulated on separate scans. (B) Tactile motion with a visual task, (C) hMT+ visual motion localizer, and (D) lateralized MT/MST visual motion localizer. Stimuli were presented to the left and right visual field on separate scans. (E) Visual motion with and without a visual task.

stimulation conditions (motion, static, and fixation) was presented. The three conditions were cycled in a fixed order (motion, static, and fixation). Every participant performed two scans. Each scan lasted approximately 5 min, and included 30 10-s blocks.

Lateralized MT/MST visual motion localizer. The lateralized visual stimuli (Fig. 1D) used to delineate MT from MST consisted of blocks of moving and static dots presented either to the left or to the right of a fixation cross (Huk et al., 2002; Beauchamp et al., 2007). Each dot

subtended 0.15° (dot density 2 per degree). Participants were asked to fixate throughout the scan and performed no task. Dots were restricted to a peripheral circular aperture (radius 7°) with its closest edge 10° from fixation. To compensate for our limited horizontal visual angle, the fixation was presented 3° off-center, and roughly half of the circular aperture was presented (see Fig. 1D). This design was chosen with the two goals of limiting stimulation of receptive fields spanning the midline and using a stimulus that extended to as far peripheral as possible.

Each block lasted 10 s, during which one of the three visual stimulation conditions (motion, static, and fixation) was presented. The three conditions were cycled in a fixed order (motion, static, and fixation). Each scan lasted approximately 5 min, and included 30 10-s blocks. Right and left visual fields were stimulated in separate scans. Every participant performed four scans, two for each visual field. One subject performed two additional scans, resulting in a total of three scans for each hemifield.

Visual motion, with and without a visual task. Finally, for one subject, we examined the effect of the Simon© task on visual motion responses (Fig. 1E). The same visual dots stimulus used for the hMT+ localizer was presented for 24-s periods of motion separated by a 12-s fixation block. Note that only motion and fixation conditions were included here, with the intention to match the conditions used in tactile stimulation (see above). Each scan lasted 6 min, and included 10 24-s motion blocks and 10 12-s resting blocks. The participant performed four scans, two that included a passive fixation spot and two that included the Simon task.

Data analysis

Data were analyzed using Brain Voyager QX (Version 2.3, Brain Innovation, Maastricht, the Netherlands) and MATLAB (Mathworks, MA). Prior to statistical analysis, functional data underwent preprocessing steps that included 3D motion correction (trilinear sinc interpolation), slice scan time correction (cubic spine), linear trend removal, and high pass filtering to remove nonlinear low-frequency drifts using a standard GLM approach implemented with BrainVoyager that uses a Fourier basis set consisting of 2 cycles of sines/cosines as predictors for lower frequencies (BrainVoyager Users Guide: Temporal High Pass Filtering). No spatial smoothing was applied to functional data.

For each individual participant, preprocessed functional data were co-registered to their corresponding anatomical data. The initial alignment was based on header information from functional and anatomical sessions and fine-tuning alignment was gradient-based (rigid body affine transformation). Anatomical and functional data were then transformed and up-sampled into Talairach space (Talairach and Tournoux, 1988) at $1 \times 1 \times 1$ mm resolution (trilinear interpolation).

ROI selection

Responses to the visual motion localizer stimulus and the lateralized visual motion localizer and the criteria used to define hMT+, MT, and MST are included within Supplementary Materials. Briefly, hMT+ was defined functionally based on the full-field hMT+ visual motion localizer as a contiguous region near the posterior part of the inferior temporal sulcus that activated significantly ($q(FDR) < 0.05$) for moving vs. static dots. MT and MST ROIs were defined as subregions of hMT+ using criteria very similar to those of Huk et al. (2002).

Beta weights were then estimated for all experimental conditions within these ROIs in Brain Voyager using a fixed effects standard generalized linear model with baseline z normalization. Beta weights are condition-associated coefficients that quantify the potential contribution of each condition in explaining the voxel time course (BrainVoyager Users Guide: The General Linear Model). Further custom analyses were carried out using custom software written in MATLAB (Mathworks, MA).

Results

Individual surface maps

Our first goal was to examine the location of tactile responses with respect to hMT+ and its subregions, MT and MST (see Supplementary

Fig. 1). Fig. 2 shows responses on the cortical surface to tactile motion. In the no-visual task condition, all subjects except S2 showed significant responses to the tactile motion stimuli in a location close to the expected location to hMT+. However, individual surface maps reveal only limited overlap between visual and tactile motion: S1 (who had exceptionally robust responses to the visual motion stimuli), showed large amounts of overlap between tactile and visual responses for both hemispheres. S4 showed a small amount of overlap for both hemispheres. S2, S3, and S5 showed minimal or no overlap between tactile and visual motion responses. The tactile responses close to hMT+ generally (except for S1) persisted in the presence of a visual distraction task, although to a reduced extent. Only in S4 in the left hemisphere was there any overlap between tactile responses and hMT+ in the absence of a visual task.

Beta weights

Although the surface maps shown in Fig. 2 reveal little overlap between regions selective for tactile and visual motion, it remains possible that tactile motion responses were present within visual ROIs, but did not reach threshold. The leftward panels of Fig. 3 show beta weights for tactile motion with and without a distractor visual task, within each of the ROIs defined by the visual motion. For comparison, responses to contralateral visual stimulation are also shown. The corresponding time courses in percent signal change are shown in Fig. 4.

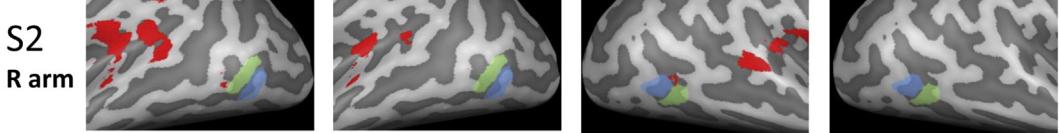
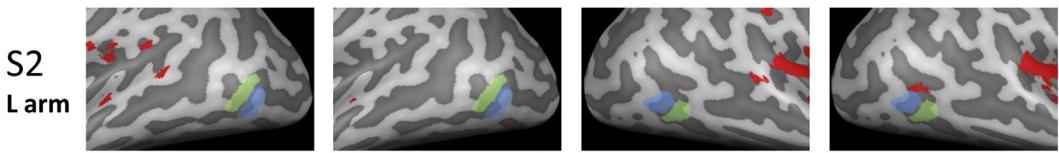
To our surprise, given the previous literature, when subjects were blindfolded and there was no visual task, there was no suggestion of sub-threshold positive tactile responses in either MT or MST. Indeed, tactile stimulation in the absence of a visual task resulted in a slight suppression of BOLD responses within visually defined MST. In the presence of a visual task, tactile responses resulted in positive responses in MT and MST, though comparison with visually evoked motion responses indicates that although these positive responses were robust (as evidenced by relatively high p values and medium to large effect sizes), they were small in magnitude. We found an extremely similar pattern of results using ROIs defined using a variety of thresholds of $q(FDR) < 0.1$, $q(FDR) < 0.01$ and Bonferroni-corrected 0.05 (data not shown). Similar results were also obtained using an STS visual motion ROI defined as showing significant responses to the hMT+ full-field localizer but being non-contiguous with hMT+ (see Supplementary Fig. 2, leftward panel), suggesting that our failure to find tactile responses in hMT+ was not due to an overly stringent definition of hMT+.

A three-way ANOVA carried out on beta weight responses in each ROI to tactile stimulation, with task vs. no task, arm of tactile stimulation (RA vs. LA), and hemisphere (RH vs. LH) as factors. For MT and MST, there was a significantly significant main effect of task (MT: $F(1, 32) = 12.36, p < 0.01$; MST: $F(1, 32) = 22.17, p < 0.001$). No statistically significant main or interaction effects for arm of stimulation or hemisphere were found for either ROI.

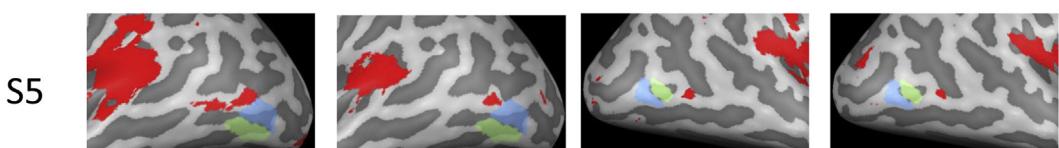
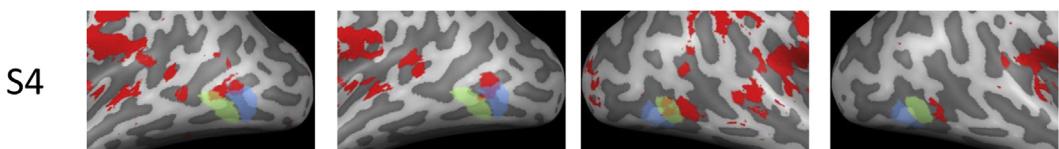
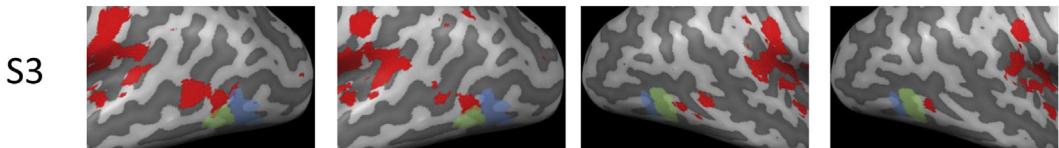
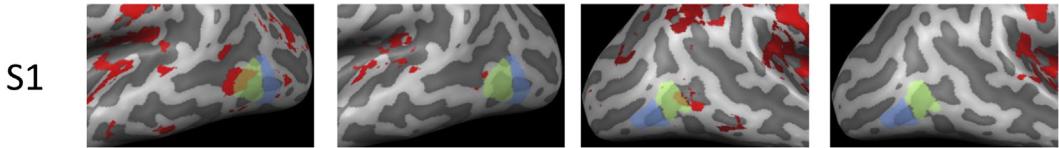
Because we found a main effect of task, but no effect of either arm of stimulation or hemisphere, we also examined whether responses were significantly different from zero after collating across both stimulation arm and hemisphere. When there was no visual distractor task, beta weights were significantly lower than zero in MST (no task, MST: mean = -0.073 , std = 0.092 , $t(19) = -3.451, p < 0.01$, $d = -0.7857$). When there was a visual distractor task, beta weights were significantly larger than zero in both ROIs (visual task, MT: mean = 0.055 , std = 0.055 , $t(19) = 4.439, p < 0.001$, $d = 0.9930$; MST: mean = 0.047 , std = 0.06 , $t(19) = 3.525, p < 0.01$, $d = 0.7880$).

To help interpret these results, we ran a single subject on a visual motion stimulus with and without the Simon task. As expected, the response to visual motion in hMT+ was consistently smaller in the presence of the Simon task (data not shown).

Tactile responses from S2 shown for each arm of stimulation



Tactile responses from remaining 4 subjects shown collapsed across arm of stimulation



No visual task Visual task No visual task Visual task

LH

RH

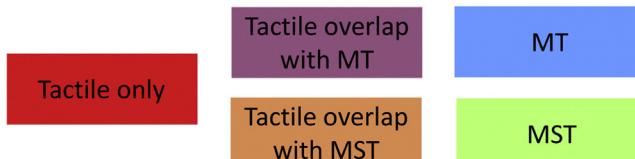


Fig. 2. Cortical surface maps for tactile responses for the no visual task and visual task conditions. Upper panels show responses from a single subject for left and right arm separately. Lower panels show responses in the remaining 4 subjects, with responses collapsed across left and right arms such that voxels were considered responsive to tactile stimulation if they responded to tactile stimulation of either the left or the right arm vs. rest ($q(FDR) < 0.05$) is shown in red, MT is shown in blue, MST is shown in green. Overlap between tactile responses and MT and MST are shown in purple and orange respectively.

Overlap between visual and tactile responses

One possibility was that the lack of positive response to tactile motion within areas sensitive to visual motion might possibly be due to only small subregions showing significantly positive responses to tactile motion. To examine this, we calculated the percentage of overlap between visual and tactile motion responses. This was simply calculated as the percentage of voxels within each ROI that showed significant responses to tactile stimulation on either arm. Data shown in the rightward panels of Fig. 3 are based on a significance level of $q(FDR) < 0.05$ for both visual and tactile motion. We found an extremely similar pattern of results using alternative thresholds of $q(FDR) < 0.1$,

$q(FDR) < 0.01$ and Bonferroni-corrected 0.05 (data not shown). Similar results were also obtained for an STS visual motion ROI defined as showing significant responses to the hMT+ full-field localizer but being non-contiguous with hMT+ (see Supplementary Fig. 2, rightward panel), suggesting that our failure to find overlap between tactile responses and visual motion responses in hMT+ was not due to an overly stringent definition of hMT+.

It should be noted that it is difficult to estimate what overlap between neighboring but non-overlapping tactile and visual motion responses might be expected simply due to false positives, shared vasculature, and the smooth spatial structure of the BOLD signal. Simulations (based on Genovese et al., 2002; Chumbley and Friston, 2009)

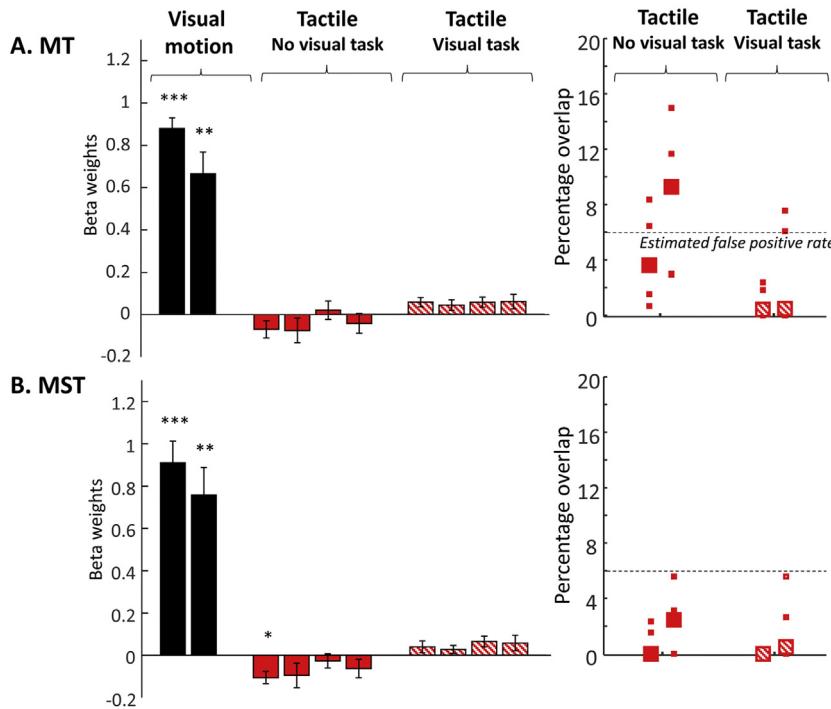


Fig. 3. Leftward panels show beta weights for tactile responses within MT and MST. For comparison, responses to the contralateral visual motion stimulus are shown for each ROI (black bars). Responses in the absence of a distractor visual task are shown in red, and responses in the presence of a distractor visual task are shown with red hatched bars. Data are shown separately for left and right hemispheres, and for left and right arms of stimulation. Each bar represents data averaged across subjects and single standard error bars are shown. Asterisks represent whether responses were significantly different from zero. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Rightward panels show the percentage of voxels within MT and MST that responded to tactile motion with and without a visual task. Again, voxels were considered to respond to tactile motion if they showed significant responses to tactile stimulation of either the left or the right arm vs. rest. The dotted line represents the number of voxels that might be expected to respond to tactile stimulation simply as a consequence of false positives.

suggest that a false positive rate of 6% is a reasonable estimate given that we included any voxels that responded to either left or right arm stimulation. Except for MT in the no-task condition, most subjects showed levels of overlap less than 6%.

Estimates of spatial blur from (Aquino et al., 2012) suggest adjoining regions can produce statistically significant spurious overlap over a surface distance of 5 mm. Except for S1, all the cases of overlap found in Fig. 3 that fell above the 6% false positive threshold, were within this 5 mm boundary, making it impossible to exclude the possibility that the apparent overlap in MT in the no-task condition found for some subjects was simply due to fMRI spatial blur. Thus, we find little evidence of overlap between visual and tactile responses in most individual subjects.

Group average responses

Our next concern was that our findings of extremely limited overlap with hMT+ might be an artifact of our particular task, which involved stimulating the arm with a brush. Although this choice of task was deliberately chosen as a replication of a previous study (Hagen et al., 2002), it was possible that other tasks might elicit tactile responses that overlapped more substantially with hMT+.

To examine this, we analyzed our data using group averaging methods, as has been used in several previous studies. Fig. 5 (panels A and B) show group-averaged data from our study (thresholded at $q(FDR) < 0.05$) based on tactile motion responses reported in Fig. 2. Even though, as described above, these data fail to show convincing overlap between visual and tactile motion in individual subjects, there is clear (spurious) overlap when the data is group-averaged. In this no-task condition, using the individual subject approach of Fig. 2, an average of 6.4% of voxels within hMT+ showed significant responses to tactile stimulation on either arm (averaged across subjects and hemispheres). However, when data is analyzed using the group-averaging

techniques (as in Fig. 5) 15.2% of voxels in hMT+ are spuriously identified as responding to tactile stimulation at a significance level of $q(FDR) < 0.05$. Although the presence of a visual task reduced the extent of group tactile motion responses near hMT+, spurious overlap between visual and tactile motion remained (12.9%).

The location and extent of tactile responses found within hMT+ when using a group-averaged approach also looks remarkably similar to the results of previous studies, as illustrated by the two examples in panels C and D (as well as others (Beauchamp et al., 2007)). Panel C shows group average data from Ricciardi et al. (2007) in a study in which subjects passively experienced Braille-like tactile flow patterns on the finger. Panel D shows group-averaged data of van Kemenade et al. (2014). In this study, subjects had to identify the direction of motion of Braille-like tactile stimulation to the fingertip. In all these datasets, the center of group-averaged tactile motion is anterior and superior to visually localized MT and MST.

Thus, while we cannot exclude the possibility that our failure to find tactile responses overlapping with visually responsive areas was unique to our particular stimulation paradigm, our results do show that it is easy to generate the spurious appearance of cross-modal responses in hMT+ on the basis of group-averaged responses even in the absence of convincing genuine overlap within individuals.

Discussion

As described in the Introduction, it has been argued that regions within hMT+ may be supramodal, with the role of processing motion regardless of the sensory modality in which it is presented (Pascual-Leone and Hamilton, 2001; Ricciardi et al., 2014). Our goal in this study was to further examine this hypothesis by replicating a previous study examining tactile responses within hMT+ and neighboring regions. In particular, we were interested in the location of tactile

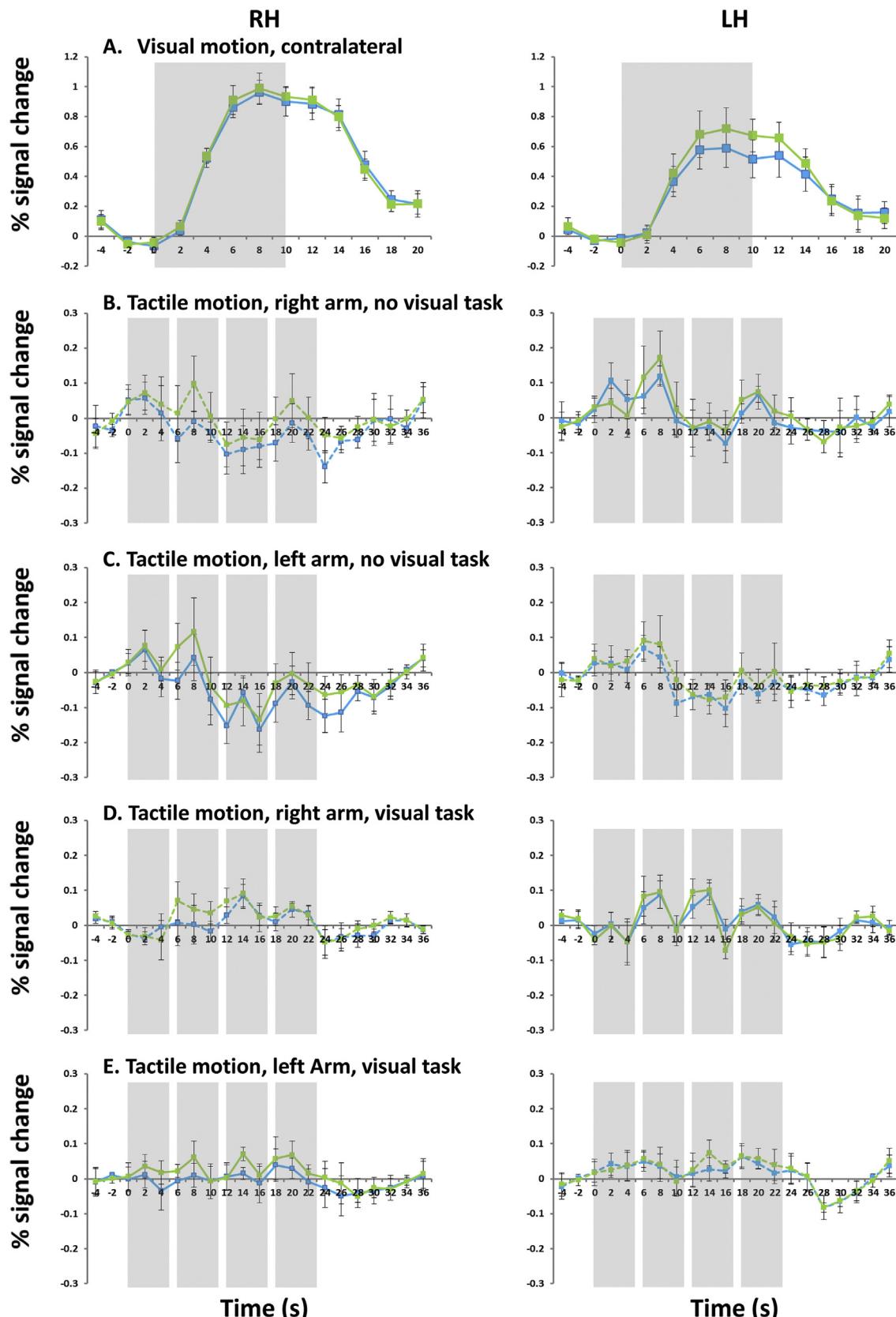


Fig. 4. fMRI time course in percent signal change within MT and MST for contralateral visual motion stimulus (A), tactile motion stimulus without a visual task (B: right arm; C: left arm), tactile motion stimulus with a visual task (D: right arm; E: left arm). Note that scale on the y-axis was changed for all tactile conditions. Leftward panels show time course data in right MT and MST, and rightward panels show time course data in left MT and MST. MT is shown in blue and MST is shown in green. Solid lines show contralateral stimulation, and dashed lines show ipsilateral stimulation. Shading represents the period of visual/tactile stimulation (10 s block for visual stimulation, 24 s block for tactile stimulation consisting of 4 5-s brushes).

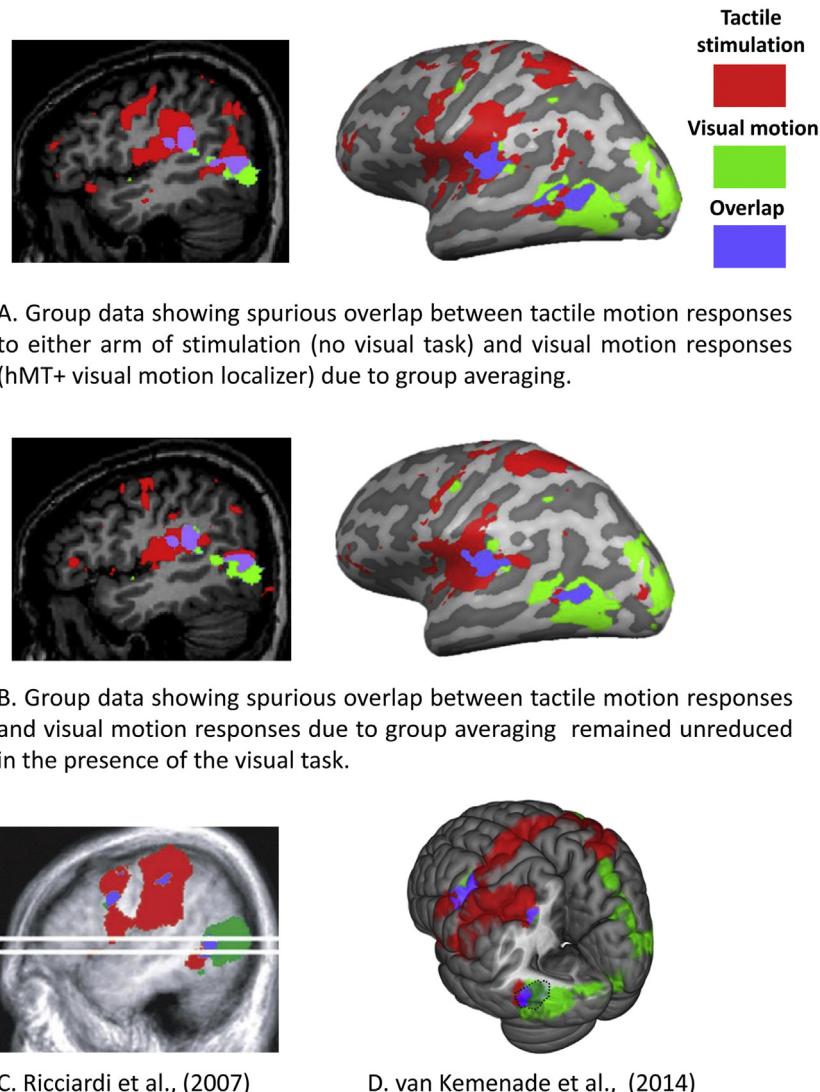


Fig. 5. The potential for spurious overlap between visual and tactile activation due to group averaging. Activation patterns are recolored so as to be consistent across all figures. Red shows tactile responses, green shows visual motion responses, and purple shows regions of overlap. (A, B) Group average tactile motion responses from the no visual task condition (C) and the visual task condition (D) reported in Fig. 2, showing regions that responded to stimulation of either arm. Data are thresholded at $q(\text{FDR}) < 0.05$. (C) Group average data reprinted from (Ricciardi et al., 2007). Tactile stimulation was via Braille-like dot patterns on a plastic surface undergoing translational and rotational tactile flow. Data are thresholded at $z > +/− 3.5$. (D) Group average data reprinted from (van Kemenade et al., 2014). Subjects performed a tactile motion direction discrimination task on moving Braille-like dot stimuli applied bilaterally to the fingertip. Data are thresholded at FWE $p < 0.05$. The dotted line shows the estimated location of hMT+.

responses with respect to MT and MST, and whether tactile responses would be found after withdrawal of attention from the tactile stimulus.

To our surprise, when individual data were examined, our findings did not replicate those of the original study: only one of the five subjects showed evidence for overlap between tactile and visual motion responses, and that overlap only occurred in the absence of a visual distractor task. Group-averaging did result in significant spurious overlap, suggesting that group-averaged results comparing overlap between conditions should be interpreted with caution for cortical regions that show significant variability in location.

Previous studies examining tactile responses in hMT+

A range of findings have been reported regarding responses to tactile activation in hMT+ that range from strong tactile activation to weak suppression. One possible reason for this wide range of findings is that a continuum of methods to define hMT+ have been used in the literature: stereotactic coordinates (Matteau et al., 2010; Wacker et al., 2011), group-averaged response to visual motion localizers (Ricciardi et al., 2007; Summers et al., 2009), and finally using individual responses to

visual motion to define hMT+ for each subject (Hagen et al., 2002; Blake et al., 2004; Beauchamp et al., 2007; van Kemenade et al., 2014). The choice of method used to define hMT+ is critical because although it has a relatively consistent position in relation to the sulcal patterns, its stereotaxic location is highly variable (Dumoulin et al., 2000). Indeed, the Jülich probabilistic atlas for hMT+ is never higher than 50% (Wilms et al., 2005; Eickhoff et al., 2007; Malikovic et al., 2007). As shown in Fig. 5, this variability can produce considerable apparent overlap between tactile and visual motion responses using a group averaging approach, even in the absence of overlap within individual subjects.

The two studies that identified hMT+ using a stereotaxic definition of hMT+ found positive responses to tactile stimulation within left stereotaxic hMT+ (Wacker et al., 2011) and bilateral positive responses within regions described as being within left and right hMT (Matteau et al., 2010). However, in both studies, the peaks of the identified region actually fell outside two standard deviations of the expected variance in the location of individually defined hMT+ (based on Dumoulin et al., 2000), though the location of peak activity being outside hMT+ does not exclude the possibility that activity extended to within the expected location of hMT+.

The studies that used group-averaged responses to visual motion stimuli to define hMT+ tended to find positive responses to tactile motion that ranged from small but significant (Summers et al., 2009) to a combination of strong positive and negative responses to tactile motion (Ricciardi et al., 2007; reanalyzed Sani et al., 2010). In the case of Summers et al. (2009), the peak coordinates of tactile activity in the right hemisphere fell within hMT+, but the region identified as left hMT+ fell outside the expected location of hMT+. In the case of Ricciardi et al. (2007), the peak coordinates of the region that showed positive activation to tactile stimulation fell outside the expected location of hMT+, whereas clusters in each hemisphere that showed suppression to tactile stimulation fell within the expected location of hMT+ in both hemispheres (Sani et al., 2010).

Several studies defined hMT+ individually using visual motion localizers and found positive modulation of hMT+ by tactile stimulation within individually defined ROIs. However, these responses have tended to be smaller than those found in the studies described above (Hagen et al., 2002; Blake et al., 2004; Beauchamp et al., 2007; van Kemenade et al., 2014). Our finding of a weak suppressive effect of tactile stimulation in the no-task condition has also previously been observed (Ricciardi et al., 2007; Lewis et al., 2010). (Interestingly, a variety of studies show suppression of hMT+ when subjects attend to an auditory motion stimulus Lewis et al., 2000; Strnad et al., 2013; Jiang et al., 2014).

A primary goal of this study was to very carefully define hMT+, including its subdivisions into MT/MST. To do this, we carried out two sessions devoted specifically to visual motion stimuli. This is more than any previous study, all of which have defined hMT+ based on less than 20 min of fMRI data (Blake et al., 2004; Beauchamp et al., 2007; van Kemenade et al., 2014) or 2–4 PET scans (Hagen et al., 2002). We believe that this likely led to a more accurate localization of hMT+ as evidenced by the close correspondence between regions defined as hMT+ across the two types of motion localizers (see Supplementary Fig. 1) and across a range of thresholds ($q(FDR) < 0.1$, $q(FDR) < 0.01$ and Bonferroni corrected 0.05).

We also collected two full fMRI sessions of tactile data for each subject. Again, this was a considerable amount of data compared to most previous studies. It can be seen in Fig. 2 that the pattern of activation across the two sessions of tactile data are very similar, though the extent of activation is highly reduced in the presence of a visual task. Thus, we believe we were successful in obtaining the high-quality data needed to accurately determine which regions are activated by tactile and visual motion, respectively.

hMT+ fails to respond to auditory motion

One might expect a supramodal hMT+ to also respond to auditory motion. However, a variety of studies have explicitly looked for, but failed to find, evidence of auditory motion responses in hMT+ (Lewis et al., 2000, 2010; Saenz et al., 2008; Bedny et al., 2010; Alink et al., 2012; Jiang et al., 2014). Indeed, in an analysis closely analogous to that of Fig. 5, it has been previously been shown by Saenz et al. (2008) that spurious auditory motion responses in hMT were elicited as a result of using group averaging methods to define hMT+. However, inspection of that same data using individual hMT+ ROIs (based on individual visual functional localizers) demonstrated that the vast majority of individually defined hMT+ ROIs did not respond to auditory motion.

Only two studies have found auditory responses in hMT+, and both may have failed to accurately isolate hMT+. Poirier et al. (2005) reported hMT+ BOLD responses to auditory motion stimuli in blindfolded sighted subjects using a definition of hMT+ based on group averaging in stereotaxic coordinates. However, among individuals, only 2 of the 8 reported coordinates of activated clusters fell within 2 standard deviations of the expected location of hMT+ (also see Watson et al., 1993; Dumoulin et al., 2000). Using multivoxel pattern analysis, Strnad et al. (2013) recently showed that while the overall BOLD response to

auditory motion was negative (in contrast to the Poirier et al. study described above, but similar to many auditory studies that used individual localizers), a region defined as hMT+ did contain classification information about different auditory motion conditions. However, hMT+ was defined as all voxels within a relatively generous 10 mm radius from MNI group peak coordinates, and classification was carried out using only 50 out of ~1000 voxels in the ROI. Thus, this analysis is likely to be highly susceptible to the inclusion of voxels from areas adjoining hMT+.

The effect of attention

Within individual subjects, in the absence of the visual distractor, task responses were slightly suppressed, though this effect was only significant in MST. In the presence of a visual distractor task, tactile stimulation elicited small but significantly positive responses in MT and MST.

What is the substrate of these modulations of hMT+ by tactile stimulation? Our finding of slight suppression of hMT+ in the absence of a visual task, and small positive responses within hMT+ with the addition of a visual task excludes a number of possibilities including: (1) a general arousal effect, (2) visual imagery, or (3) a direct response to tactile motion stimuli within hMT+. All these explanations would predict a larger response within hMT+ in the absence of a visual task.

One possibility is that tactile responses are the result of featural and/or cross-modal attention. In one subject, we confirmed that the presence of the Simon task served to reduce BOLD responses to the visual motion stimulus. Attending to the Simon task in isolation may reduce hMT+ BOLD responses more effectively than the Simon task in the presence of the tactile brush. There are many reasons that this might be the case: for example, the tactile motion stimulus contains the shared feature of motion, the Simon task was extremely demanding, so the addition of tactile stimulation may have 'released' some attention, or withdrawing visual spatial attention might be more effective at reducing hMT+ BOLD responses than withdrawing cross-modal attention to a tactile stimulus (Ciaramitaro et al., 2007). Thus, the modulation of hMT+ by the presence or absence of tactile stimulation may reflect the effects of cross-modal attention rather than signifying tactile responses within hMT+ per se. This explanation is also consistent with the fact that no primate electrophysiology paper to date has reported tactile responses in MT/V5: Presumably cross-modal attentional effects of tactile stimulation would be less likely to be casually observed than increases in spiking as a direct result of tactile stimulation.

Limitations of our findings

Given our small number of subjects, our findings cannot be taken as evidence that no individuals show responses to passive tactile stimulation in hMT+ (indeed, one of our five subjects did show such responses in the absence of a visual distractor task). However, our results do suggest that these responses do not occur in the majority of individuals. We also only examined a single tactile task. Although we deliberately chose arm brushing because our goal was to replicate a previous influential positive finding in the literature, it is nonetheless possible that tactile stimulation of other body parts might be more effective in eliciting responses in hMT+.

Finally, our goal was to examine whether hMT+ is 'supramodal'—processing motion regardless of the sensory modality in which it is presented (Ricciardi et al., 2014). Consequently, we chose to replicate a paper that used a passive protocol for tactile stimulation that was related to the prediction for supramodal responses. Supramodal responses should be driven by the sensory stimulus itself, and therefore should be observable during passive stimulation and survive (albeit attenuated) withdrawal of attention to a visual stimulus. It remains perfectly likely that asking subjects to actively perform a tactile direction discrimination task (or some equivalent) would lead to enhanced

hMT+ responses to tactile motion. Similarly, our results do not address whether hMT+ shows multisensory interactions: whether the response to a visual stimulus in hMT+ is influenced by the presence of a congruent or incongruent tactile stimulus, as suggested by Blake et al. (2004).

Summary

Here, we present data from a replication of Hagen et al. (2002). In contrast to that study, we did not find that passive tactile stimulation consistently activated hMT+. We also present analyses showing that failing to accurately localize hMT+ can easily lead to artifactual responses to tactile motion within hMT+, which may have contributed to positive findings in previous studies. Although the presence of tactile stimulation did produce a small modulation of responses in hMT+, the pattern of responses with respect to the withdrawal of attention was the opposite of what would be predicted if these small modulations were due to direct tactile motion responses in hMT+, as compared to cross-modal featural attention. Thus, the evidence for supramodal responses in hMT+ may be less conclusive than has sometimes been assumed.

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