

Role of the Superior Temporal Region in Human Visual Motion Perception

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While moving objects are usually seen using luminance (first-order) cues, humans can perceive the motion of objects via non-luminance (second-order) cues. Contrary to previous case reports, no physiological studies have elucidated distinct differences in the cortical regions involved in first- and second-order motion processes. We investigated brain responses related to these two types of motion perception in human subjects using 3 T functional magnetic resonance imaging and strictly controlled apparent motion stimulus pairs. Comparison of brain activation to moving versus static states of each motion stimulus isolated cortical activity related to each type of motion perception. We found a selective neural response to second-order motion stimulus in the anterior part of the superior temporal sulcus (STS) contralateral to stimulus presentation and cue-invariant activation of MT/V5+. No significant activation in the STS was observed by the first-order motion, even when its visibility was reduced to levels comparable to that of second-order motion. Furthermore, the STS demonstrated significant activation for highly visible motion stimulus with both first- and second-order attributes. The STS represents the cardinal structure for perception of second-order motions, although further studies are needed to elucidate the exact neural process occurring in this area.

Keywords: first-order motion, functional magnetic resonance imaging, motion-defined motion, second-order motion

Introduction

We usually perceive the motion of objects by luminance differences from the background (first-order cues). Brightness or darkness, however, can change dramatically in the real world: sunlight may be diminished by clouds and moving objects may be hidden in shadow. Numerous studies have found that humans possess distinct mechanisms to detect motion based on non-luminance information (second-order cues) (Derrington and Badcock, 1985; Chubb and Sperling, 1988; Cavanagh and Mather, 1989; Lu and Sperling, 2001).

Despite our obvious ability to perceive second-order motion, controversy exists regarding the location for processing of second-order information in the human brain (Johnston *et al.*, 1992; Mareschal and Baker, 1998; Baker, 1999). Neurophysiological studies in monkeys have indicated that neurons in MT or V5, which are considered specialized for motion perception, show similar directional selectivity irrespective of motion cues (Albright, 1992; O'Keefe and Movshon, 1998). In addition, subpopulations of neurons in the early visual area (V1 and V2) can encode moving objects in a cue-invariant (CI) manner (Chaudhuri and Albright, 1997; Bourne *et al.*, 2002). These results indicate that, although first- and second-order motions may be processed in distinct ways, integration of these

processing results is achieved in the very early stages in the visual cortex.

Recent neuroimaging studies on humans support this view. Although several neuroimaging studies have reported second-order selective regions in the human cerebral cortex (Smith *et al.*, 1998; Dumoulin *et al.*, 2003), these studies did not compare motion-specific brain responses (activation differences between moving and static conditions of each stimulus) for first- and second-order stimuli. According to a previous study using functional magnetic resonance imaging (fMRI) (Seiffert *et al.*, 2003), this lack of static control exerts a serious influence on imaging results. This is because brain activation detected by direct comparison of first- and second-order moving patterns may reflect differences in visual features of these stimuli (e.g. visual complexity or lifetime of moving objects), rather than differences in brain responses involved in first- and second-order motion perception. In many imaging studies with static controls, no brain regions could be found selectively related to second-order motion processing (Claeys *et al.*, 2003; Dupont *et al.*, 2003; Seiffert *et al.*, 2003).

These results are, however, somewhat inconsistent with the results of human neuropsychological studies. Vaina *et al.* (1999) described a double dissociation of first- and second-order motion processing impairment. The lesion in a patient with second-order deficit was located in the superior temporal sulcus (STS). Another study reported several cases with parietal and occipito-temporal lesions in which direction discrimination of second-order motion was selectively impaired (Plant *et al.*, 1993). These studies indicate the existence of cortical regions other than the striate cortex that are specialized for second-order motion processing.

There are several possible reasons for this discrepancy in previous studies of second-order motion perception. First, most previous neurophysiological and neuroimaging studies have focused predominantly on brain responses within the classical visual cortical areas (Chaudhuri and Albright, 1997; Smith *et al.*, 1998; Bourne *et al.*, 2002; Nishida *et al.*, 2003; Seiffert *et al.*, 2003). While such procedures enable detailed investigation of activation within the visual areas, second-order specific responses in the higher cortical regions might be diminished or overlooked by this limitation of regions-of-interest (ROIs). Second, although several recent studies have investigated whole brain responses (Claeys *et al.*, 2003; Dupont *et al.*, 2003), two motion stimuli with differing visual characteristics (e.g. white-dot motion in static black background versus global shift of texture-micropatterns against flickering background) were used to provide first- and second-order cues, rendering strict comparison of these two types of motion uncertain (Dumoulin *et al.*, 2003).

The present fMRI study explored whole-brain activation in response to strictly controlled motion stimulus pairs used in our previous study (Sofue *et al.*, 2003). Our second-order cue involves motion speed of dots in a random-dot kinematogram (RDK). Whereas moving objects in the first-order motion condition (1ST) stimulus comprise dots brighter than those in the background (Fig. 1A), the second-order motion condition (2ND) uses dots moving faster than the others (Fig. 1B). One advantage of this speed-modulated second-order cues over conventional second-order cues (contrast-modulated motion, etc.) is that the present stimulus is theoretically free from potential first-order artifacts suggested in a previous study (Smith and Ledgeway, 1997). This is because detection of the present stimulus cannot be explained by simple input nonlinearity of luminance transduction systems (Zanker and Burns, 2001). By comparing brain responses elicited by these two types of motion stimuli, we sought to identify cortical areas beyond the striate cortex selectively involved in second-order motion processing.

Materials and Methods

The present study consisted of two experiments. In the main experiment, we searched for brain regions specifically related to second-order motion perception using three apparent motion stimuli (1ST, 2ND and 1ST-low), as well as the lowest control condition (random dot motion condition, RDM) to identify cortical areas involved in general motion

perception. In additional experiment, we further employed three types of motion stimuli with second-order attributes (MIX, FLC and 2ND-R) and investigated the various characteristics of second-order brain regions detected in the main experiment.

Subjects

Seventeen individuals (seven women, ten men) participated in the two most important conditions (1ST and 2ND) in the main study where brain responses to first- and second-order cues were measured and compared. The remaining five conditions were conducted on subsets of the 17 subjects (the number of subject in each condition was summarized in Tables 1 and 2). All subjects displayed normal or corrected-to-normal visual acuity. Informed consent was received from each participant after the nature of the studies had been explained. Approval for these experimental protocols was obtained from the ethical committee of the National Institute for Physiological Sciences, Okazaki, Japan.

Visual Stimuli in the Main Experiment

Motion stimuli in 1ST, 2ND and 1ST-low conditions were presented through an RDK field subtending a visual angle of $11.7^\circ \times 11.7^\circ$ (180×180 pixels) on the projector screen at a viewing distance of 30.5 cm. Dot density of the stimulus was always 10%, with one dot corresponding to a single pixel brighter than the RDK background. Each dot jumped a certain distance (1 or 3 pixels) either up, down, right, or left at a refresh rate of 60 Hz, corresponding to a dot speed of $3.9^\circ/s$ and $11.7^\circ/s$, respectively.

Three types of apparent motion (1ST, 2ND and 1ST-low) of a rectangular area ($1.5^\circ \times 5.2^\circ$) were presented against random dot movement in the background area (Fig. 1). In 1ST, the moving object

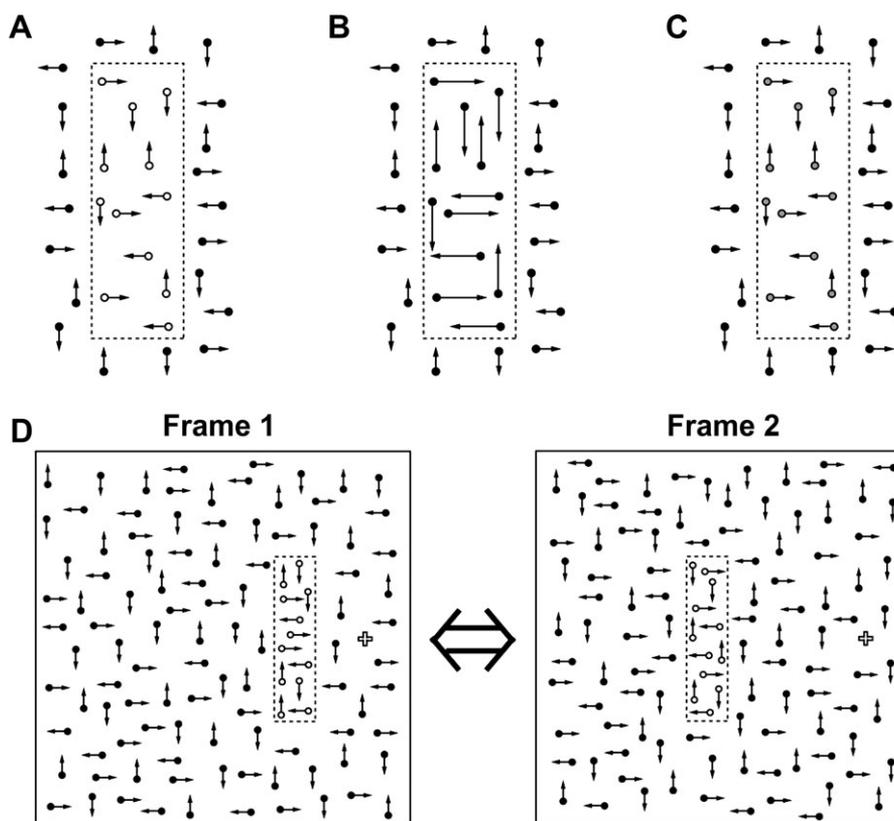


Figure 1. Schematic illustrations of the three apparent motion stimuli used in the present study. All apparent motions were presented in the left visual field and motion distance was 3° . (A) Object in first-order motion stimulus (1ST). The object (rectangle, shown as area enclosed by broken line, subtending $1.5^\circ \times 5.2^\circ$) in apparent motion was defined by brighter moving dots (open circles) than those in the background (filled circles). Rectangle contour depicted by the broken line is only for the purposes of illustration. (B) Object in second-order motion condition (2ND). Vector length represents motion speed of each dot. Dots within the rectangle move three times as fast as those in the background, although luminance of all dots is identical. (C) Object in the 1ST-low condition. As in the 1ST condition, dots within the rectangle are brighter than those in the background. However, difference in luminance between rectangle and background was reduced in this condition, to align motion visibility with that in 2ND. (D) Apparent motion presentation. Alternate presentation of these two frames with no inter-frame interval induces apparent motion perception of the rectangle (motion epoch). Although this figure shows only the frames in the 1ST conditions, there are three types of apparent motions according to the three moving objects in A–C.

Table 1
Stimulus conditions used in this study

Stimulus	Motion	Order (cue)	Visual field	Subjects
RDM	local smooth motion	first	left	15
1ST	apparent motion	first	left	17
2ND	apparent motion	second (speed)	left	17
1ST-low ^a	apparent motion	first	left	15
MIX	apparent motion	first and second (speed)	left	13
FLC	apparent motion	second (flicker)	left	12
2ND-R	apparent motion	second (speed)	right	15

^aFirst-order cue in the 1ST-low stimulus is weaker than that in 1ST.

Table 2
Subjects in seven conditions

Subject	Conditions						
	RDM	1ST	2ND	1ST-low	MIX	FLC	2ND-R
S1	*	*	*	*	*	*	*
S2	*	*	*	*	*	*	*
S3	*	*	*	*	*	*	*
S4	*	*	*	*	*	*	*
S5	*	*	*	*	*	*	*
S6	*	*	*	*	*	*	*
S7	*	*	*	*	*	*	*
S8	*	*	*	*	*	*	*
S9	*	*	*	*	*	*	*
S10	*	*	*	*	*	*	*
S11	*	*	*	*	*	*	*
S12	*	*	*	*	*	*	*
S13	*	*	*	*	*	*	*
S14	*	*	*	*	*	*	*
S15	*	*	*	*	*	*	*
S16		*	*		*		
S17		*	*				
Total	15	17	17	15	13	12	15

*S1-S17: 17 subjects employed in the present study. Each subject was scanned only once for each condition.

(rectangle) was defined by brighter dots (mean luminance, rectangle area 65.5 cd/m²; background area 45.8 cd/m²), but all dots moved at the same speed (Fig. 1A). In contrast, the rectangle in 2ND was defined by higher dot speed (11.7°/s compared to 3.9°/s for background dots), while luminance of all dots remained identical (Fig. 1B). As both 1ST and 2ND stimuli are produced in the RDK display and share a common background, the only difference between these two motions lies in the definition of the rectangle (luminance versus speed, respectively) that apparently moves.

However, previous studies have indicated that visibility of second-order cues is generally lower than that of first-order cues (Smith *et al.*, 1998; Nishida *et al.*, 2003). To control for this aspect, we introduced another type of first-order motion (Fig. 1C, 1ST-low) in which luminance of dots within the rectangle was decreased relative to 1ST stimulus. Due to the reduced difference in luminance between moving object and background, motion visibility in 1ST-low is much lower than that in 1ST. If brain activities found to be selective for 2ND were due to low visibility of the stimulus, and not perception of the second-order attribute (speed) itself, these activities should be also elicited in the 1ST-low condition. Although no task (passive viewing) was used during fMRI, the preliminary experiment described below (Behavioral Experiment Procedures) was conducted to align motion visibility of 2ND and 1ST-low stimuli (Fig. 2).

In each of these three conditions, motion-related brain responses were isolated by comparing 'motion' and 'control' epochs. In the 'motion' epoch, the rectangle appeared 1.5° left from the fixation point in one frame and 4.5° left in the other (Fig. 1D). Alternate presentation of these two frames induces a perception of apparent motion between the two positions (3° from each other). Duration of each frame was 1 s and no inter-frame interval was used. In the 'control' epoch, another frame was presented in which two rectangles appeared simultaneously

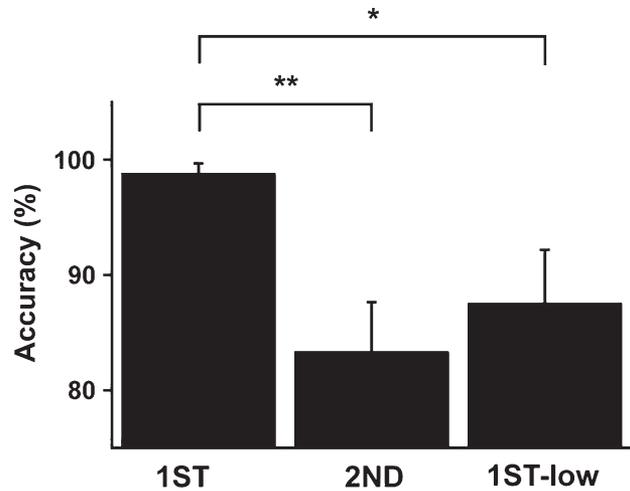


Figure 2. Behavioral accuracy of the direction discrimination task conducted on the 1ST, 2ND and 1ST-low apparent motions. As motion direction is either left or right, chance level of the task is 50%. Although significant differences in accuracy existed between 1ST and the other 2 conditions (1ST versus 2ND $t = 3.74$, $P < 0.01$; 1ST versus 1ST-low $t = 2.49$, $P < 0.05$), no difference was observed between 2ND and 1ST-low ($t = 1.68$, $P > 0.05$). * $P < 0.05$; ** $P < 0.01$ (paired t -test).

and continuously while all dots continued to move. This epoch controlled for the local movement of dots and the perception of rectangular shapes defined by respective attributes, without inducing a perception of apparent motion.

To identify brain regions involved in general motion perception, we introduced a fourth motion condition (RDM) in which incoherent (random) motion of dots was compared with the static state. This stimulus was selected because it has been used in numerous visual motion studies and was also used to measure the activity in the human putative MT/V5+ (McCarthy *et al.*, 1995). In the present study, we used a random-dot field with the same size and position as those in apparent motion conditions (thus, presented in the left visual field of subjects). Dot density is 10% and each dot (1 bright pixel) moved either up, down, right or left at a speed of 3.9°/s. Mean luminance of the field was 45.8 cd/cm². These parameters were also identical to the background dots in the apparent motion conditions.

Behavioral Experiment Procedures

Apart from fMRI, a behavioral experiment was conducted to align motion visibility of the 1ST-low and 2ND stimuli. This experiment comprised two procedures. Initially, strength of luminance cue in the 1ST-low condition was adjusted based on subjective visibility of that stimulus. Moving objects (rectangles) of the 1ST-low and 2ND conditions appeared simultaneously over a single RDK background, and subjects were instructed to answer which rectangle was easier to see (forced-choice). The psychophysical staircase method was used to identify luminance of the 1ST-low rectangle judged to have the 'same' visibility as the 2ND rectangle. Luminance of the 1ST-low rectangle systematically varied according to subject responses, while all features in backgrounds and 2ND rectangle were fixed. The point of subjective iso-visibility was calculated by averaging the last two reversal points in the luminance time series of the 1ST-low rectangle.

Using the iso-visible luminance of the 1ST-low rectangle as determined above, a direction discrimination experiment for apparent motion stimulus was then conducted. In this experiment, apparent motion of each of the 1ST, 2ND and 1ST-low rectangles was presented at a random timing and subjects were asked to judge direction of apparent motion (left or right) with a button press (forced-choice). Apparent motion comprised two frames (Fig. 1D) and the size and position of rectangle and background in addition to the fixation point were also identical to those in the fMRI experiment, although display duration of each rectangle was reduced to 100 ms to avoid the ceiling effect of task performance. As apparent motion is presented in a random timing, subjects cannot answer the direction correctly unless they see both

frames and make a judgment regarding the temporal order between frames. Trials of the 1ST, 2ND and 1ST-low apparent motions were randomly intermixed and 24 trials were used for each of the three conditions.

fMRI Data Acquisition and Analyses

All fMRI experiments were conducted using a conventional block design with a 3 T MRI system (Allegra, Siemens). The four types of motion stimuli were tested in separate runs. In all conditions, subjects were instructed to stare at a fixation point in the central visual field. In each acquisition run of 246 s, the initial control epoch (21 s) was followed by five repetitions of the motion epoch (24 s) and its control epoch (21 s). Order of conditions was counterbalanced across subjects. Using a gradient echo-planar imaging (EPI) sequence [repetition time (T_R), 3000 ms; echo time (T_E), 30 ms; flip angle, 80°; field of view, 192 × 192 mm²; resolution, 3 × 3 mm²], over 48 slices of 3 mm thickness with 0 mm gap were scanned to cover the entire brain volume. In a single run, 83 volumes were obtained following three dummy images. To normalize individual brains into a standard brain, a three-dimensional structural brain image of each subject was also obtained using an MP-RAGE sequence (Mugler and Brookeman, 1990) with the following parameters: T_R , 2500 ms, T_E , 4.38 ms, flip angle, 8°, field of view, 230 × 230 mm², resolution, 0.9 × 0.9 mm².

Data analyses were performed using SPM99 (statistical parametric mapping software; Wellcome Department of Cognitive Neurology, London, UK) (Friston *et al.*, 1995) on MATLAB (Math Works, Natick, MA). Initially, functional volume data for each subject in multiple runs were realigned to the first image. Each individual brain was normalized to the standard brain space defined by the Montreal Neurological Institute with re-sampling of 2 mm using bilinear interpolation. Normalized data were then spatially smoothed using an isotropic Gaussian kernel of 8 mm full width at half maximum (FWHM). Temporal filters were also applied and low frequency noise and global changes in the signal were removed. Specific effects for motion perception were estimated for each subject using a general linear model with a boxcar waveform convolved with a canonical hemodynamic response function (Friston *et al.*, 1998). Group analysis (random-effect model) of each stimulus condition was then performed by entering contrast images into one-sample *t*-test. Statistical threshold was set at $P < 0.001$, uncorrected for multiple comparisons (no significant activation could be found in all seven conditions when we set our threshold at $P < 0.05$ corrected). Activation clusters <10 voxels were further removed. Direct comparisons between two motion conditions (e.g. 1ST versus 2ND in Fig. 4A) were also conducted using paired (or two-sample) *t*-tests of contrast images in each condition.

Regarding brain areas significantly activated in group analysis, ROI analyses were conducted using the MarsBaR toolbox for SPM99 (developed by Brett, Anton, Valabregue, and Poline, available online at <http://marsbar.sourceforge.net/>). Initially, ROIs (all significantly activated voxels within each cluster) were defined based on the results of group analysis. This ROI information was then applied to individual functional data after normalization and a mean signal percent change within each ROI was calculated for each condition of each subject.

Motion Stimuli in the Additional Experiment

According to several previous psychophysical studies, there is an interaction effect of first- and second-order motion processing (Harris and Smith, 2000; Smith and Scott-Samuel, 2001; Zanker and Burns, 2001). For example, Smith and Scott-Samuel (2001) reported improved perceptual accuracy when first- and second-order cues were combined in a single motion stimulus. If this is true, the brain regions found to be involved in second-order motion processing are highly likely to be activated when cue-mixed stimuli are presented, because processing of the second-order cue in those regions may underpin behavioral improvements under cue-mixed condition. To test this hypothesis, we introduced a MIX condition (Fig. 6A, left panel) where the rectangle was defined by both first- and second-order attributes, with dots in the rectangle brighter and moving faster than those in the background. Due to the combination of luminance and speed cues, this stimulus had the highest visibility among all apparent motion stimuli in the present study.

Although second-order motion in the present study was defined by speed differences between dots in object and background areas,

previous lesion studies in humans have reported second-order selective impairments using other types of second-order motion, such as flicker-defined or contrast-defined one (Vaina *et al.*, 1999; Vaina and Soloviev, 2004). To examine consistency with previous case report, we made an apparent motion stimulus of flicker modulation (FLC, right panel of Fig. 6A). In this condition, the moving object (rectangle) and background were depicted using a black-and-white random pixel pattern, not an RDK field. Pixels within the rectangle were dynamic while those in the background remained static, with subjects perceiving apparent motion of the rectangle based on this static-dynamic contrast. Size and position of the rectangle and background were identical to those in other apparent motion conditions. We also investigated cortical regions activated by contrast-defined apparent motion stimuli. No area in the whole brain was found to be significantly activated in contrast to previous studies using continuous motions, although all our subjects perceived vivid motion for this stimulus. This discrepancy could be partly due to contamination of first-order cues in contrast-defined second-order motion (Smith and Ledgeway, 1997). The reason significant activation was not seen even in MT/V5+ using contrast-defined apparent motion is under investigation using magnetoencephalography (MEG).

A recent fMRI study by Claeys *et al.* (2003) reported that the inferior parietal lobule (IPL) of human brains shows selective activation with higher-order (third-order) motion processing based on saliency tracking of a moving object. Interestingly, this area responds to the higher-order motion stimulus presented in bilateral visual fields, not in a contralateral manner as other traditional regions for motion perception. As the 'higher-order' motion they studied differed from the second-order motion presently investigated, examination of whether our second-order selective region display bilateral or contralateral representation would be interesting. We therefore added a new condition where the 2ND stimulus was presented in the right visual field of subjects (2ND-R), rather than the left. The comparison of brain activation in 2ND and 2ND-R conditions would reveal a laterality of the second-order motion region identified in the main study.

The procedures for fMRI scanning of these three motion conditions, such as structure of motion and control epochs, were identical to those in apparent motion conditions of the main experiments. The features in all seven motion conditions and the number of subjects who participated in each condition were summarized in Tables 1 and 2.

Results

Behavioral Data

Behavioral accuracy of the direction discrimination task is shown in Figure 2. While task performance in the 1ST stimulus was significantly higher than the other two conditions, no difference in accuracy was identified between 2ND and 1ST-low ($t = 1.68$; $P > 0.05$). These results indicate that motion visibility of these two conditions is controlled both subjectively and objectively.

Functional Imaging Results in the Main Experiment

Figure 3A shows brain responses to the RDM condition in which static and dynamic states of RDK were compared. As predicted from previous neurophysiological and neuroimaging studies, significant activation was observed in early visual cortex and occipito-temporal regions at the boundary of Brodmann's areas 19 and 37, corresponding to the human homologue of MT/V5+ (Zeki *et al.*, 1991; Tootell *et al.*, 1995). These activities were highly lateralized to the hemisphere contralateral to stimulus presentation. Brain regions showing significant activation to the 1ST, 2ND and 1ST-low apparent motion stimuli were then identified (Fig. 3B). The 1ST stimulus induced significant activation in several regions in the cerebrum and cerebellum, although activation in early visual areas observed in the RDM condition was not detected in the 1ST condition, probably due

to the continuous presentation of dynamic random dots throughout the motion and control epochs in this condition. The most distinct responses were found in the right MT/V5+ and precentral gyrus (PrCG) (Fig. 3B, upper panel). These two regions also showed significant signal increases in the 2ND condition, but additional activity was found in two other regions outside the occipital area: the angular gyrus (AG); and the STS (Fig. 3B, middle panel). The 1ST-low stimulus, on the other hand, elicited strong activation in the PrCG (Fig. 3B, lower panel), in addition to relatively weak activation in the fusiform gyrus. Neural responses in MT/V5+ did not reach significance ($P = 0.002$) although the signal increase was similar to the 1ST and 2ND (Fig. 5B), probably due to a decrease in luminance cue under this condition and a small scale of apparent motion response itself in MT/V5+ by the continuous local dot motion in the control period. These results in 1ST-low condition indicate that neural responses of AG and STS in the 2ND condition are not due to low visibility of the 2ND stimulus. Particularly in the

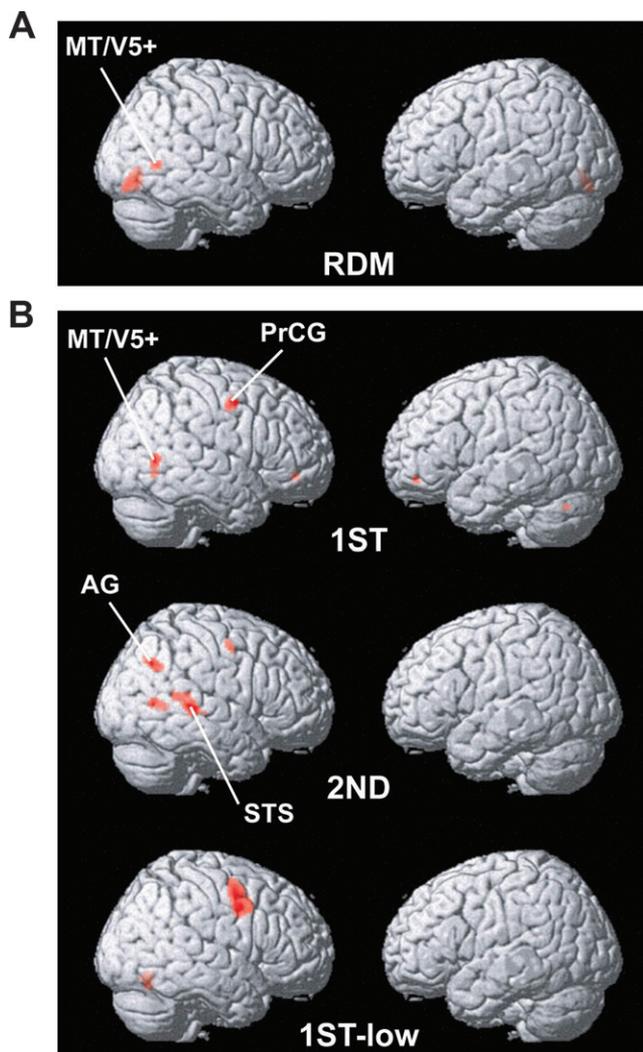


Figure 3. Brain responses in four conditions. (A) Results in RDM condition. Brain activation in response to dynamic random dots presented in the left visual field was compared with response to static dots. Using SPM99 software, all activated regions were rendered on the surface of a standard brain. (B) Significantly activated brain regions in 1ST, 2ND and 1ST-low conditions. Brain responses in the motion epoch of each condition were compared with those in the control epochs. Other details are the same as (A). Note the 2ND-selective activation in the STS and AG areas.

STS, significant differences were also obtained in direct comparisons between 1ST versus 2ND (Fig. 4A) and 1ST-low versus 2ND (Fig. 4B), emphasizing the crucial role of this region in second-order motion processing. The difference in activation patterns of the 1ST and 2ND conditions was clearly seen in single slice images (Fig. 5A). Stereotactic coordinates and t values for all local maxima in the 4 conditions are summarized in Table 3. No medial activation was observed except in the early visual area under RDM condition and in the fusiform gyrus under 1ST-low condition.

Functional Imaging Results in the Additional Experiment

Based on the results from direct comparison of 1ST (-low) and 2ND (Fig. 4), response characteristics in the STS region were investigated using various motion stimuli with second-order attributes. Both the STS and MT/V5+ were significantly activated under MIX condition (Fig. 6B). As the MIX stimulus offers the highest motion visibility of all the conditions, significant STS activation in the MIX provides additional evidence for our view that this region responds to second-order attributes irrespective of visibility of the motion stimulus. Furthermore, STS was strongly activated also under FLC conditions (Fig. 6B), which is consistent with the results of a previous lesion study (Vaina and Soloviev, 2004). A direct comparison of motion-related signal changes between FLC and 1ST (and 1ST -low) conditions, however, failed to reach significance ($P > 0.05$). Finally, using 2ND-R conditions, the STS was found to display contralateral, not bilateral, representation of second-order motion processing (Fig. 7, left panel). This result is also consistent with the previous lesion study reporting that a patient with a selective impairment of second-order motion processing showed no

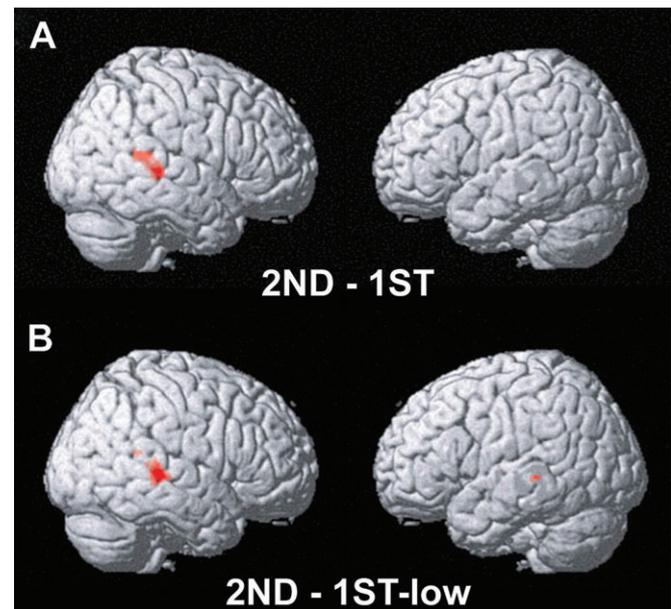


Figure 4. Direct comparison between motion conditions. (A) Comparison of 1ST and 2ND conditions with inclusive masking of 2ND activation ($P < 0.001$, uncorrected): significant voxels in both 2ND-1ST contrast and in the 2ND condition (Fig. 3B, middle panel) are shown. (B) Comparison of 1ST-low and 2ND conditions with inclusive masking of 2ND activation ($P < 0.001$, uncorrected). In both contrasts, a significant 2ND selectivity was observed in the right STS. Although our statistical threshold was $P < 0.001$ (uncorrected), the threshold was lowered at $P < 0.05$ (uncorrected) only for this figure for display purposes.

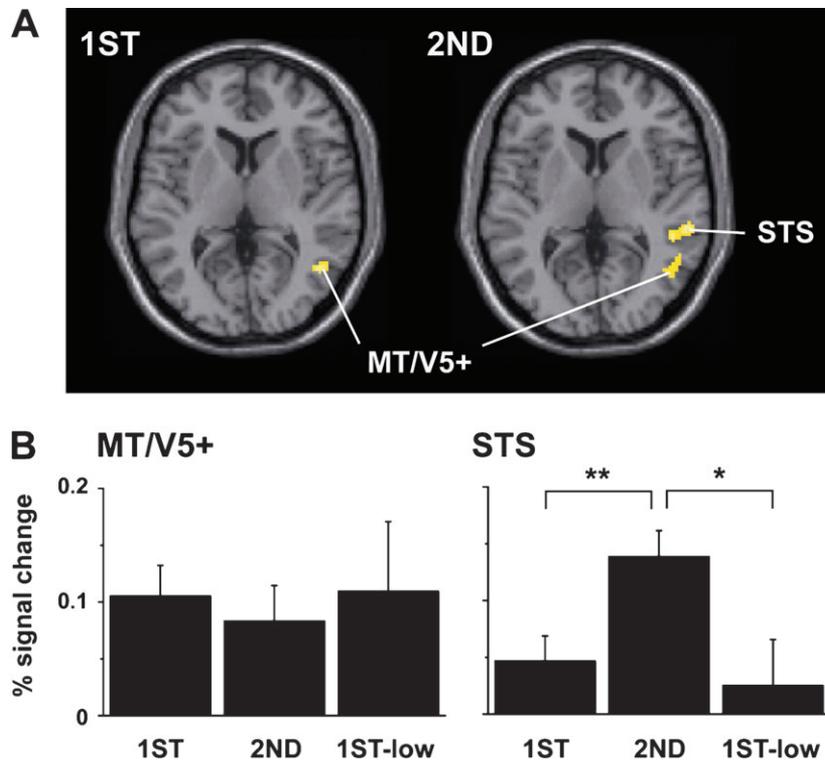


Figure 5. Neural activation in MT/V5+ and STS regions. (A) Axial slices illustrating differences in activation patterns in the 1ST (left) and 2ND (right) conditions. Both slices are parallel to the anterior commissure-posterior commissure (AC-PC) line, $z = 6$ (slice 6 mm above AC-PC line). (B) Mean percentage signal change over all significantly activated voxels in MT/V5+ and STS, calculated for each condition. In this and subsequent figures, the percentage signal change means a BOLD signal increase or decrease during the motion epoch of each stimulus condition as compared to its control epoch. Activation clusters (ROIs) for MT/V5+ and STS were defined based on SPM results of group-analysis in RDM and 2ND conditions, respectively (Fig. 3A,B middle panel). Error bars denote standard error (SE) across subjects. $*P < 0.05$; $**P < 0.01$ (paired or two sample t -test).

Table 3
Activated regions in four motion conditions

Region	BA	Hemisphere	X	y	z	t
RDM						
Middle temporal gyrus (MT)	37	R	46	-62	2	6.4
Lingual gyrus	18	R	16	-82	-10	5.9
1ST						
Middle temporal gyrus (MT)	37	R	50	-62	2	5.0
Precentral gyrus (PrCG)	6	R	44	-6	46	5.4
Middle frontal gyrus	11	R	32	44	-8	4.2
		L	-30	48	-10	4.3
Cerebellum		L	-32	-66	-30	4.4
2ND						
Middle temporal gyrus (MT)	37/39	R	46	-60	10	4.4
Precentral gyrus (PrCG)	6	R	48	-4	50	4.9
Superior temporal sulcus (STS)	22/42	R	58	-34	4	5.5
Angular gyrus (AG)	39	R	44	-60	34	5.7
1ST-low						
Precentral gyrus (PrCG)	6	R	52	2	42	6.5
Fusiform gyrus	19	R	26	-66	-14	5.3

BA, Brodmann's area near the coordinates; L, left hemisphere; R, right hemisphere.

impairment when second-order motion was presented in the ipsilesional field (Vaina *et al.*, 1999).

We also applied these ROI analyses to the AG area, another second-order selective region in the main experiment (Fig. 3B). No significant activation was found in all conditions ($P > 0.05$ for all). These results and direct comparisons in Figure 4 indicate that the neural activation in the AG region is not so much specialized for second-order motion perception as the

STS, although the AG may be involved in the processing of some types of second-order motion.

Comparison with Previous fMRI Results on Higher-order Motion Perception

A recent study by Claeys *et al.* (2003) conducted a detailed investigation of cortical activation to first-, second- and higher-order motion stimuli. While no region was reported selectively related to second-order motion perception, higher-order (third-order) motion processing was found in the IPL of human brains in addition to first-order selective activation in various brain regions. In particular, the first-order selective area in the posterior STS (pSTS) was close to the STS site identified in the present study, although we confirmed that no anatomical overlap exists between the activation cluster in our STS site and the pSTS coordinate reported previously. We therefore plotted the signal percent change in the IPL and STS regions under 1ST and 2ND conditions to compare the present and previous results. The IPL region in the present study showed no significant activation in both 1ST and 2ND conditions (Fig. 7, middle panel), and no differences were observed between activation levels in these two conditions. These results indicate that 2ND-selective activation in the STS site represents a motion-processing channel separate from that in the higher-order IPL region. Furthermore, the fact that the between-condition difference is also not significant in the pSTS site (Fig. 7, right panel) suggests functional segregation between our STS and previous pSTS regions. However, a greater percentage signal change in the 2ND than 1ST was still observed in

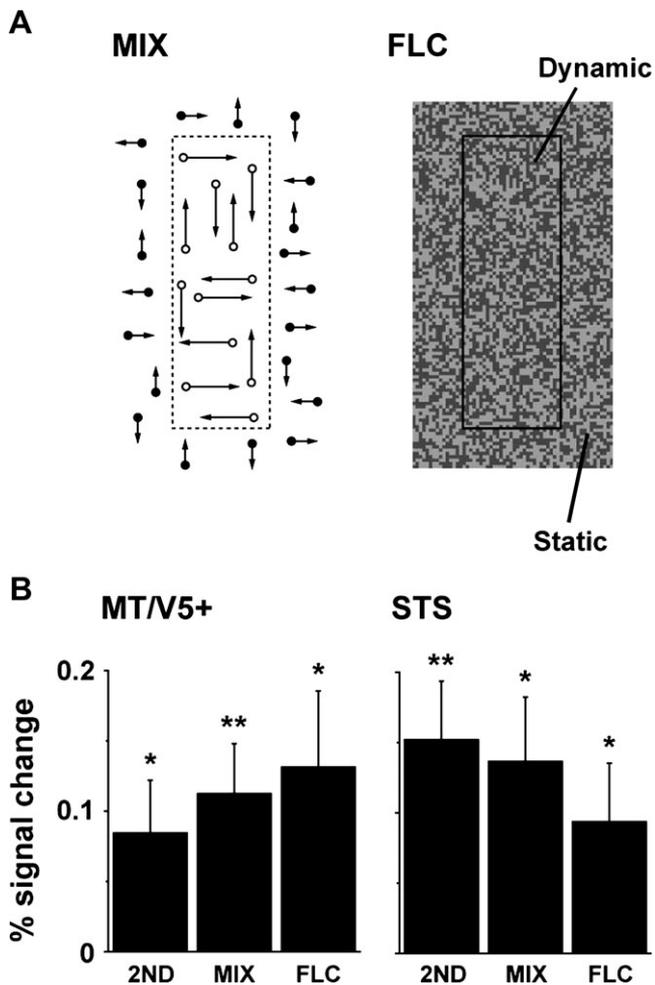


Figure 6. Stimuli and results under MIX and FLC conditions. (A) Moving objects under MIX (left) and FLC (right) conditions. In MIX, dots in the rectangle are brighter and move faster than those in the background. In FLC, pixel pattern within the rectangle changes dynamically at 60 Hz, while the background remains static. Other details such as structure of motion and control epochs were identical to other apparent motion conditions (1ST, 2ND, 1ST-low). (B) Signal percent changes (mean \pm SE) in MT/V5+ (46, -58, 2) and STS (58, -34, 12) areas. As in the 2ND condition, MIX and FLC stimuli induced significant activation in both MT/V5+ and STS regions. * $P < 0.05$; ** $P < 0.01$ (one sample *t*-test)

the pSTS, which may indicate that functional profiles in our STS and pSTS areas are not completely independent from each other. One possible reason for the similarity of two regions is an imprecise pSTS location in the present study because of the several differences in our experimental procedures (e.g. subjects) from those in Claeys *et al.* (2003).

Discussion

The present study conducted a strictly controlled comparison of brain responses to first- and second-order motion stimuli. The most distinct activation selective for second-order motion perception was found in the STS contralateral to stimulus presentation. Control experiments demonstrated that strong STS activation under second-order motion conditions could not be explained by low visibility of second-order stimulus. Moreover, the STS showed significant activation in response to various second-order cues in other motion stimuli.

Involvement of Third-order or Long-range Motion Mechanisms

One characteristic of the present motion stimuli is that we employed first- and second-order apparent motion stimuli rather than the smooth motions conventionally used. Although this was based on our previous finding that these apparent motions induced distinct brain responses rather than smooth ones (Sofue *et al.*, 2003), one may argue that our apparent motion stimuli could activate long-range motion mechanisms (Braddick, 1974) or the third-order motion detection system (Lu and Sperling, 1995; Lu and Sperling, 2001), rather than the neural system for second-order motion processing. However, apparent motion is a common feature of 1ST and 2ND stimuli, and thus long-range or third-order motion systems would be required in both 1ST and 2ND conditions. Explaining 2ND-selective activation in the STS by recruitment of these systems is therefore difficult. Furthermore, regarding the third-order motion system, a recent fMRI study (Claeys *et al.*, 2003) reported that apparent motion with high temporal frequency (7 Hz) induced significant activity in the IPL (their third-order motion region), while IPL activation in response to 2 Hz apparent motion was comparable to that in the control condition where no apparent motion could be perceived. Given the low temporal frequency of apparent motion used in the present study (1 Hz) and the fact that significant activation in the IPL was not actually found in all conditions, the apparent motion aspect of the present stimuli appear unlikely to have activated the third-order detection system in the human brain. Therefore, differences in methods of defining moving object (luminance under 1ST conditions and speed under 2ND conditions) must have elicited the significant activation of the STS, although involvement of other motion detection systems cannot be excluded conceptually.

STS and Motion Processing

Using our apparent motion stimuli of the motion-defined area, we showed activation of the STS specific to the second-order cue, which cannot be due to the low visibility of the second-order motion. Although we found significant activation of the STS by the other second-order apparent motion of flicker-defined area (FLC), its percentage signal increase was not significantly different from those for the 1ST and 1ST-low. Together with the lack of significant activation in contrast-defined condition, these results indicate that the second-order selectivity of the STS becomes distinct particularly in the motion-defined motion condition and would be relatively difficult to be generalized to other types of second-order motions. Another possibility is that the higher level of STS activity would be required for the processing of motion-defined motion than other second-order motions because of the explicit preprocessing necessary for the detection of motion-defined motion (Zanker and Burns, 2001) even though the STS is cardinal structure for the perception of any second-order motions.

While our present results indicate that the STS is selectively related to second-order motion processing, this region has also been shown to be involved in other types of visual motion perception. In particular, many previous studies have indicated close relationships between biological motion processing and neural activation in the superior temporal region (Puce *et al.*, 1998; Allison *et al.*, 2000; Vaina *et al.*, 2001; Grossman and Blake,

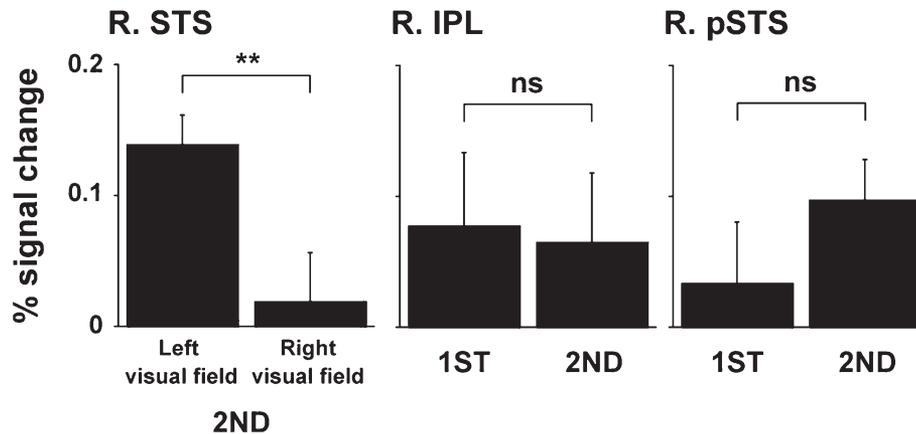


Figure 7. Activation profiles in right STS, right IPL and right pSTS regions. In the left graph, mean signal percentage changes within the activation cluster of the STS, the same ROI as Figure 5B (right), were plotted. Regarding the right IPL and right pSTS, regional coordinates (60, -34, 30 for right IPL; 56, -48, 6 for right pSTS) were determined based on previous reports by Claeys *et al.* (2003). Error bars denote SE across subjects. $**P < 0.01$ (two sample *t*-test); ns, non-significant.

2002). Considering these previous studies, our present results suggest that the STS is implicated not only in second-order motion perception, but also in higher visual motion processing in general, although this possibility was not directly examined in the present study. Further studies must be aimed to elucidate how the neural processing of second-order motion is related to that of other types of higher motion perception.

Comparison with a Previous MEG Study

In a previous MEG study (Sofue *et al.*, 2003), we investigated neuromagnetic responses related to second-order motion perception using the same apparent motion stimuli as the present study. Taking advantage of the fine temporal resolution of MEG, the previous study reported differences in neural response latency to 1ST, 2ND and MIX stimuli. Latency of the 2ND response in MT/V5+ was found to be significantly longer than that of the 1ST, while latency in MIX was between those of the 1ST and 2ND. Conversely, MT/V5+ demonstrated cue-invariant activation in the present fMRI study (Fig. 3) and 1ST and 2ND induced comparable activation in this area (Fig. 5B). These results indicate that, although both types of motion perception surely employ the neural system in the MT/V5+, processing mechanisms for these two motions are dissociated before reaching MT/V5+. Results in the present fMRI study suggest that one potential region of this pre-MT/V5+ stage in second-order motion perception may be located in the STS, even though this area seems upstream of MT/V5+, considering the anatomical distance from the primary visual cortex and histological findings in monkey brains (Felleman and Van Essen, 1991). To our knowledge, however, there has been no clear evidence demonstrating a feedback signal from STS to MT, although MT and the superior temporal polysensory area are known to be reciprocally connected by way of MST (Boussaoud *et al.*, 1990; Cusick *et al.*, 1995). Additionally, anatomical (and functional) differences between monkey and human brains should be considered, especially for STS region (Orban *et al.*, 2004), in order to compare the present and previous neurophysiological results.

Contribution of Early Visual Areas on Second-order Motion Perception

It should be noted that our results do not preclude the existence of second-order processing systems in other brain

regions, particularly within early visual areas. In all apparent motion conditions in the present study, local dot motion was kept dynamic in both motion and control epochs. Since it is well established that V1 and V2 neurons show significant responses to moving dots as compared to stationary dots (Dupont *et al.*, 1994; Tootell *et al.*, 1995; Sinaert *et al.*, 1999), our continuous presentation of local dot motion would induce saturation of activity for these neurons and obscure activation differences in early visual areas between the two epochs, even if neurons in these areas have the ability to process second-order motion. Peripheral presentation of our motion stimuli might also diminish V1 responses where receptive fields of many neurons are allocated to the central visual field. Given the mounting evidence that neurons in V1 and V2 encode the direction of second-order motion (Chaudhuri and Albright, 1997; Bourne *et al.*, 2002), the second-order cortical area reported in the present study (e.g. STS and MT/V5+) may detect second-order motion in close collaboration with neurons in the early visual cortex. Although this hypothesis never goes beyond a speculation at this time because there has been no clear evidence supporting it, potential interactions of STS or MT/V5+ with other second-order detection systems in response to various types of second-order motion stimuli need to be studied in future investigations.

Previous Neuroimaging Studies on Second-order Motion Perception

There have been several previous studies of PET and fMRI investigating the neural mechanisms of second-order motion processing (Smith *et al.*, 1998; Claeys *et al.*, 2003; Dumoulin *et al.*, 2003; Dupont *et al.*, 2003; Nishida *et al.*, 2003; Seiffert *et al.*, 2003). Regarding the studies focusing on occipital visual regions (Smith *et al.*, 1998; Nishida *et al.*, 2003; Seiffert *et al.*, 2003), it is difficult to compare their results with ours due to the continuous local dot motion in the present study as described above. On the other hand, some consistency of the results could be found between the current data and previous studies exploring the whole brain activation (Claeys *et al.*, 2003; Dumoulin *et al.*, 2003). Dumoulin *et al.* (2003) recently showed the extensive second-order selective activation over the occipital and parietal areas as well as the posterior STS region reported by Vaina *et al.* (1999). Claeys *et al.* (2003) also found a significant (but not selective) activation to second-order

motion stimuli in a region shifted ventrally (18 mm in group analysis) from their third-order motion area (R. IPL). These previous results suggest a possibility that some parts of parietal and temporal area are related to second-order motion perception, consistent with our present results in Figure 3B, although several problems in their experimental procedures such as the lack of static control or the use of different visual features across conditions (see Introduction) made interpretation of their results unclear.

Conclusions

Using apparent motion of objects defined by luminance and speed attributes, the present study showed that second-order motion processing is closely related to neural responses in the STS region, and these responses cannot be attributed to attention enhancement or perceptual difficulty involved in second-order motion perception. Although further investigation is needed to clarify how these higher cortical areas process second-order motion, the present results provide spatial information that will facilitate future elucidation of cue-independent motion processing mechanism in the human brain.

Notes

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