Close Similarity Between Spatiotemporal Frequency Tunings of Human Cortical Responses and Involuntary Manual Following Responses to Visual Motion

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Submitted 28 August 2008; accepted in final form 3 December 2008

Amano K, Kimura T, Nishida S, Takeda T, Gomi H. Close similarity between spatiotemporal frequency tunings of human cortical responses and involuntary manual following responses to visual motion. J Neurophysiol 101: 888–897, 2009. First published December 10, 2008; doi:10.1152/jn.90993.2008. Human brain uses visual motion inputs not only for generating subjective sensation of motion but also for directly guiding involuntary actions. For instance, during arm reaching, a large-field visual motion is quickly and involuntarily transformed into a manual response in the direction of visual motion (manual following response, MFR). Previous attempts to correlate motion-evoked cortical activities, revealed by brain imaging techniques, with conscious motion perception have resulted only in partial success. In contrast, here we show a surprising degree of similarity between the MFR and the population neural activity measured by magnetoencephalography (MEG). We measured the MFR and MEG induced by the same motion onset of a large-field sinusoidal drifting grating with changing the spatiotemporal frequency of the grating. The initial transient phase of these two responses had very similar spatiotemporal tunings. Specifically, both the MEG and MFR amplitudes increased as the spatial frequency was decreased to, at most, 0.05 c/deg, or as the temporal frequency was increased to, at least, 10 Hz. We also found in peak latency a quantitative agreement (~100–150 ms) and correlated changes against spatiotemporal frequency changes between MEG and MFR. In comparison with these two responses, conscious visual motion detection is known to be most sensitive (i.e., have the lowest detection threshold) at higher spatial frequencies and have longer and more variable response latencies. Our results suggest a close relationship between the properties of involuntary motor responses and motion-evoked cortical activity as reflected by the MEG.

INTRODUCTION

Visual motions evoke strong neural activities in temporoparietal area of human cortex (hMT+), which is considered to include the middle temporal area (MT) and the medial superior temporal area (MST) in monkey cortex. This has been shown by a variety of noninvasive brain imaging techniques, including positron emission tomography (Watson et al. 1993; Zeki et al. 1991), functional magnetic resonance imaging (fMRI) (Nishida et al. 2003; Tootell et al. 1995b), electroencephalography (EEG) (Bach and Ullrich 1994, 1997; Hoffmann et al. 2001), and magnetoencephalography (MEG) (Ahlfors et al. 1999; Amano et al. 2005; Anderson et al. 1996; Bundo et al. 2000). Previous imaging studies have revealed significant correlations between motion-evoked responses in this area and (conscious) visual motion perception such as the motion aftereffect (Tootell et al. 1995a; Zeki et al. 1993), implied motion (Krekelberg et al. 2003), or illusory jitter (Sasaki et al. 2002).

The correlations however are not strong enough to conclude that the observed motion-evoked activity is a direct neural correlate of motion perception. Here we highlight two dissociations between motion perception and the population neural activity measured by MEG, a technique that enables us to measure human cortical activity with high temporal resolution. First, in comparison with the spatiotemporal tuning of human visual motion sensitivity estimated from contrast detection thresholds (Burr and Ross 1982), MEG amplitude has a peak at a much lower spatial frequency and a higher temporal frequency as we describe in the following text. Second, the MEG latency is much shorter and less variable than the latency of voluntary behavioral response to the perception of stimulus onset (Amano et al. 2006).

The effects of visual motion on human behavior are not limited to conscious perception of visual motion. Visual motion is known to induce rapid and automatic motor response in the eyes, hands, and body. For instance, when a large field visual motion is suddenly presented during a reaching hand movement, the hand trajectory is changed toward the direction of motion. This manual following response (MFR) is rapid and involuntary (Saijo et al. 2005). Interestingly, the latency of MFR appears to be comparable to the latency of the motion-evoked MEG. In addition, the spatiotemporal tuning of the MFR has a peak at a very-low-spatial and high-temporal frequency (Gomi et al. 2006).

We have designed the current study to permit a direct comparison between the motion-evoked MEG response and the MFR. We measured the peak amplitude and latency of these two types of responses using the same drifting gratings with changing its spatio-temporal frequency. The spatiotemporal tuning of the MEG amplitude obtained either with or without subjects’ hand movements surprisingly resembles the spatiotemporal tuning of the MFR amplitude. In addition, the two responses have similar time courses peaking at 100–150 ms from the motion onsets. These findings suggest that behavioral correlate of the initial part of the population responses evoked by visual motion can be found in involuntary motor responses.

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METHODS

Subjects

Eight subjects (aged 25–44 yr) participated in experiment 1. Six of them participated in experiment 2. All subjects were healthy and had normal or corrected-to-normal vision. The experimental protocols were approved by the human subjects review board of NTT, and the subjects gave their informed written consent. All of the subjects are right-handed.

Visual stimuli and experimental procedure

The visual stimuli were generated using Cogent Graphics (University College London, London, UK) software operating on Matlab (MathWorks, Natick, MA), and projected by a Digital Light Processing (DLP) projector (V-1100Z, PLUS) onto a translucent screen (62 × 47 deg) located 83 cm from the subjects. The refresh rate was 60 Hz, and the pixel resolution was 800 × 640 in the first experiment and was 1,024 × 768 in the second experiment for the higher spatial frequency stimuli. The stimuli were two rectangular moving gratings (35 × 11 deg, each, in the 1st and 2nd experiments). These stimuli were presented in the upper and lower visual fields on a gray background. The lower edge of the upper stimulus and upper edge of the lower stimulus were presented in the upper and lower visual fields on a gray background. The refresh rate was 60 Hz, and the pixel resolution was 800 × 640 in the first experiment and was 1,024 × 768 in the second experiment for the higher spatial frequency stimuli. The stimuli were two rectangular moving gratings (35 × 11 deg, each, in the 1st and 2nd experiments). These stimuli were presented in the upper and lower visual fields on a gray background.

In the first experiment, we used four combinations of spatiotemporal frequencies: [spatial frequency, temporal frequency] = [0.02 c/deg, 1.6 Hz] (80 deg/s, 18 pixel/frame), [0.125 c/deg, 10 Hz] (80 deg/s, 18 pixel/frame), [0.05 c/deg, 10 Hz] (200 deg/s, 45 pixel/frame), and [0.02 c/deg, 10 Hz] (500 deg/s, 112 pixel/frame). Within the stimulus aperture (35 deg), 0.7, 1.75, and 4.4 cycle was visible for the spatial frequency of 0.02, 0.05, and 0.125 c/deg, respectively. In our previous behavioral study (Gomi et al. 2006), 0.05 c/deg was the lowest spatial frequencies, and [0.05 c/deg, 10 Hz] was the condition showing the largest MFR. Using 0.02 c/deg at two temporal frequencies allowed us to test whether the proportional increase in MFR amplitude to stimulus log-speed, which was a characteristic feature of the MFR in the ranges of 0.05–1 c/deg and 0.4–10 Hz (Gomi et al. 2006), is also observable for the extremely low spatial frequency stimuli. It should be noted that even at the highest temporal frequency (10 Hz), the phase shift per each frame was 1/6 cycle of the grating, and subjects could perceive smooth motion for all stimuli. The initial phase of the gratings was randomized across trials, with keeping 180 deg phase difference between upper and lower gratings.

With these four spatiotemporal frequencies, we measured the responses for a high contrast (50%), which is known to elicit large MFR, as well as a low contrast (3%). One reason we used multiple contrasts was to add another stimulus factor that could vary the response amplitude and latency. We also expected that the low contrast would reduce the contribution of low-level cortical activities to MEG responses (Anderson et al. 1996). The response to each contrast was measured in separate sessions, in which moving gratings (rightward/leftward) or stationary gratings were presented in random order. For each contrast, 100 trials were repeated for each moving grating (rightward/leftward) with four different spatiotemporal frequencies, and the stationary grating was presented 25 times for each condition (100 times in total). The number of presentations of stationary gratings was smaller than that for motion stimuli because we are mainly interested in the responses to moving stimuli. The moving and stationary gratings were presented in random order. To avoid motion adaptation, left and right motions were presented randomly.

MEG responses to these gratings were recorded under both passive viewing and reaching conditions in separate sessions. The MFRs were collected in another session outside of the MEG room due to technical difficulties in simultaneous measurement of MEG and hand movement. All measurements started with a presentation of stationary rectangular gratings. One second after the stationary grating presentation, a small circular flash indicating a reaching target was presented at the center of the screen for 33 ms. In the MEG measurement under the passive viewing condition, subjects just fixated the center of the screen, and the gratings started to move 0.75 s after the flash stimulus. In both the MEG measurement under the reaching condition and the MFR measurement, subjects were instructed to place the right hand at a start position (around the right lap of subject) and keep pushing a button with a finger (thumb or index) at the beginning of each trial, and to release the button to initiate reaching movement toward the flash, ~1 s (self-timed) after the flash stimulus. The grating motion started 100 ms after the button release and lasted for 320 ms. Interstimulus interval was 2.2 s. Note that the delay of the arm reaching from the flash was to prevent the contamination by the MEG responses to the flash stimulus. Because of the constraints imposed by the MEG equipment, we couldn’t place the screen within the reaching distance of subjects. Because of our preliminary experiment confirmed that the use of a stick for the reaching helps to induce the MFR, during the measurements of MEG and MFR, each subject used a stick just to touch the screen with the index finger.

In the second experiment, the MFR and MEG were recorded with 15 spatiotemporal frequency conditions with a single (50%) grating contrast. The spatiotemporal frequencies were 0.05–1.6 c/deg at 2.5, 5, 10 Hz (15 sample points). Only the passive viewing condition was tested for the MEG measurement. Experimental procedures were identical to the first experiment. Each stimulus was presented 80 trials (rightward, 40; leftward, 40), and the stationary grating was presented 10 times for each grating pattern. The 15 moving gratings and stationary gratings were presented in random order. The time course of the stimulus presentation was the same as the first experiment except that the stimulus duration was 350 ms.

MEG recordings and analysis

Brain magnetic fields were recorded in a magnetically shielded room using a whole-head MEG system (PQ2440R, Yokogawa) with 230 axial gradiometers (dBz/Hz) and 70 3-vector sensors (dB x, y, z). Data were sampled at 500 Hz with a 200-Hz low-pass filter and a 0.3-Hz high-pass filter. MEG responses were averaged with respect to the timing of motion onsets (from 300 ms before until 600 ms after the onsets) and were low-pass filtered at 40 Hz. We averaged MEG responses regardless of motion directions because motion direction had little effect on the responses. The one or two equivalent current dipole (ECD) model was used to estimate the location of activated brain regions at around the peak latency. The dipoles were accepted when they are on the gray matter and the goodness of fit (GOF) is higher than 80%. The dipole location was shown on T1-weighted MRI images, which were acquired on a 1.5 T Siemens Sonata scanner with a vendor-supplied head-coil (voxel size of 1 × 1 × 1 mm3). The x, y, and z axes were defined along medial–lateral, anterior–posterior, and superior–inferior directions, respectively. Left, posterior, and superior directions are considered to be positive.

MEG responses measured while subjects executed reaching movement inevitably include motor-related response in addition to visual response. We used two methods to exclude the response component related to the hand movement. One is to subtract the MEG response while subjects made a reaching response during the presentation of stationary stimuli (reaching only condition) from the MEG response for each moving grating. The other is to use signal space projection (SSP) (Tesche et al. 1995) to extract visual component. In this analysis, MEG responses before subtraction were decomposed into visual and motor components. The visual component was defined by the peak response of MEG under the condition without reaching, averaged across four spatiotemporal frequencies, while the motor component was defined by the peak response under the reaching only condition. Extracted time course of visual response includes neither motor response nor the visuo-motor interaction. The MEG responses under the condition without reaching were projected only onto the
visual component. In both methods, for the subtracted or extracted MEG, the root mean square (RMS) value of all sensors was calculated, and its peak amplitude and latency were compared between the conditions.

**MFR measurements and analysis**

The right-hand position (monitored by a marker placed on the back of the hand around the bottom of the ring finger) was obtained with an optical position sensor (VICON MX; Vicon UK, Oxford, UK) at 250 Hz, and the wrist motion was prevented by a simple cast. The position data were low-pass filtered at 20 Hz and were numerically time-differentiated to obtain those acceleration data. The difference of mean acceleration patterns between right- and leftward visual motion conditions (Gomi et al. 2006; Saijo et al. 2005) was calculated for each spatiotemporal frequency condition to quantify the MFR. Note that the failed trials, in which marker was not correctly detected or the arm movement pattern was extremely different from those in the identical stimulus condition, were excluded from the analysis. These outliers were detected by a threshold of three times of the 70% of the squared sum values of the deviations from the median movement velocity in each condition, which was heuristically defined. In each stimulus condition for all participants, 1.5 trials (mean) in the first experiment and 2.1 trials (mean) in the second experiment were excluded from averaging.

**RESULTS**

The time course of the MFR, evaluated by the difference between mean hand acceleration patterns of the direction parallel to the horizontal meridian of the screen in the right-and leftward visual motion conditions (Gomi et al. 2006; Saijo et al. 2005), shows a peak at around 140–200 ms for 3% contrast and at around 130–170 ms for 50% contrast (Fig. 1, A and B). Figure 2, A and B, shows separately for each stimulus condition the peak latencies and amplitudes of the MFR averaged across all eight subjects. The peak amplitudes were significantly affected by spatiotemporal frequency \( F(3,21) = 26.4, P < 0.001, 2\)-way repeated-measures ANOVA but were not affected by contrast \( F(1,7) = 0.0015, P = 0.97 \). The peak amplitude for [0.125 c/deg, 10 Hz] was significantly larger than that for [0.02 c/deg, 1.6 Hz] even though the motion speeds were the same (80 deg/s) \( t_2 = 5.6, P < 0.001 \) for 3% contrast and \( t_2 = 4.7, P = 0.002 \) for 50% contrast, Bonferroni corrected paired t-test). Additionally, although the motion speed was much higher for [0.02 c/deg, 10 Hz] (500 deg/s) than for [0.125 c/deg, 10 Hz] (80 deg/s), and [0.05 c/deg, 10 Hz] (200 deg/s), the response amplitude was significantly smaller for [0.02 c/deg, 10 Hz] \( t_2 = 4.0, P = 0.005 \) and \( t_2 = 5.1, P = 0.002 \) for 3% contrast and \( t_2 = 3.3, P = 0.01 \) and \( t_2 = 6.4, P < 0.001 \) for 50% contrast, Bonferroni corrected paired t-test). These two results seem to indicate that the stimulus log-speed proportional law of the MFR (Gomi et al. 2006) does not hold for the extremely low spatial frequencies with this stimulus size. This, however, might be partially because only 0.7 cycles of the 0.02 c/deg grating was presented on the screen, so the spatiotemporal frequency component is not restricted to the corresponding frequency and direction, which might result in a decrease in MFR.

Another notable feature of the MFR is the relationship between its latency and amplitude. The larger peak responses for [0.125 c/deg, 10 Hz] and [0.05 c/deg, 10 Hz] were accompanied by shorter peak latencies. The peak latencies were significantly faster for 50% contrast than for 3% contrast \( F(1,7) = 19.0, P < 0.001, 2\)-way repeated measures ANOVA) (Fig. 2B) and were significantly affected by spatiotemporal frequencies \( F(3,21) = 16.0, P < 0.001, 2\)-way repeated-measures ANOVA).

**FIG. 1.** Time courses of the manual following response (MFR) and magnetoencephalographic (MEG) response evoked by grating motion with four spatio-temporal frequencies, for a typical subject. The MFR (A and B) is evaluated by the difference of mean hand acceleration patterns between the right- and leftward visual motion conditions, in the horizontal direction. MEG response \( (C–F) \) is averaged for both left- and rightward motions and evaluated by the root mean square (RMS) of all sensors. **Left and right 3 panels** show the responses to 3 and 50% contrast, respectively. For the MEG response with reaching (E and F), we subtracted the response during the presentation of stationary stimuli from the responses during the presentation of each moving grating, to exclude the response component related to the hand movement. The time courses of the MFR and MEG response were very similar and were modulated similarly with the change in spatiotemporal frequencies.
Whole-head MEG response evoked by the onset of grating motion was measured while the subject passively viewed the motion stimulus without making any motor responses or while the subject made the same reaching task as performed in the MFR measurement. Figure 1, C and D, shows the root mean square (RMS) of MEG responses under the passive viewing condition averaged across trials. The MEG responses start to rise at around 50–80 ms from the motion onset, and peak at around 100–180 ms. Figure 2, C and D, show the MEG peak latency and amplitude, averaged across all subjects. The effects of stimulus spatiotemporal frequency on the amplitude and latency, averaged across all subjects. The effects of contrast and spatiotemporal frequency were around 100–180 ms. Figure 2, E and F, shows the MEG peak amplitude and latency averaged across all subjects. The MEG amplitude was significantly larger for 50% contrast than for 3% contrast \( F(3,21) = 17.2, P < 0.001 \) and latency \( F(3,21) = 7.4, P = 0.002 \) are similar to those observed with the MFR. For instance, the MEG amplitude was smallest for \([0.02 \text{ c/deg, } 1.6 \text{ Hz}] \) and largest for \([0.125 \text{ c/deg, } 10 \text{ Hz}] \) and \([0.05 \text{ c/deg, } 10 \text{ Hz}] \). In agreement with MFR, the MEG peak latency was faster for 50% contrast than for 3% contrast \( F(1,7) = 48.0, P < 0.001 \). The MEG amplitude was significantly larger for 50% contrast than for 3% contrast \( F(1,7) = 37.6, P < 0.001 \), while the contrast effect on the MFR amplitude was insignificant. For two of eight subjects \((KA, TK)\), the dipole modeling at around the peak latency fulfilled the criterion, and showed the activity around hMT+ of both hemispheres [Supplemental Fig. S1A1 \((x, y, z) = (43.2, 29.8, \text{ and } 56.2 \text{ mm}) \) and \((-40.1, 41.7, \text{ and } 49.0 \text{ mm}) \)] and the activity in V1/N2 \((x, y, z) = (-6.5, 67.9, \text{ and } 45.1 \text{ mm}) \), respectively. Iso-contour maps of the other subjects also indicate the activities in occipital and temporop-occipital areas (see Supplemental Fig. S1B for the iso-contour maps of all subjects), but the dipole modeling was not successful presumably due to the presence of multiple sources arising from stimulation of both hemispheres by a large field motion. Given the two successful estimations in the current study and a previous study showing the dipole in V1 and MT (Anderson et al. 1996), it is reasonable to assume that the MFR response at around the peak latency reflects the combination of activities in V1/N2 and hMT+.

For direct comparison of the MFR and MEG response obtained for eight stimulus conditions, MEG peak amplitude/latency was plotted against MFR peak amplitude/latency (Fig. 3, A and B). The correlation of the amplitudes was marginally significant \( r = 0.67, t_6 = 2.21, P = 0.07 \). The reason for the relatively weak correlation for the amplitudes was that the effect of stimulus contrast on peak amplitude was much weaker for the MFR than for MEG response. Within each contrast, the peak amplitudes were highly correlated \( r = 0.95, t_5 = 4.3, P = 0.004 \) for 3% and \( r = 0.91, t_2 = 3.1, P = 0.02 \) for 50%.

The peak latencies of MFR and MEG are not only highly correlated \( r = 0.93, t_6 = 6.02, P < 0.001 \) but also quantitatively very similar to each other.

Figure 1, E and F, compared across spatiotemporal frequencies, separately for each contrast, the time course of root mean square (RMS) values of the MEG under the reaching condition. The response to each motion measured during reaching was subtracted by that under reaching only condition in which stationary stimuli from the responses during the presentation of each moving grating.
significant for both amplitude [$F(1,7) = 37.9, P < 0.001$; $F(3,21) = 44.7, P < 0.001$] and latency [$F(1,7) = 51.2, P < 0.001$; $F(3,21) = 7.5, P = 0.001$]. Figure 3, C and D, shows the relationship between the peak MFR amplitude/latency and MEG amplitude/latency. Peak MEG latency was again highly correlated with MFR latency ($r = 0.94, t_6 = 6.48, P < 0.001$), and the correlation between MEG and MFR amplitudes is marginally significant ($r = 0.68, t_6 = 2.29, P = 0.062$).

The pattern of the subtracted MEG response is quite similar to that obtained under the passive viewing condition, suggesting that the motor-subtracted MEG component was dominantly visual response. The interaction between the visual response and the motor response was not clearly observed at least in the RMS of MEG response but might be included in the subtracted response. To remove the interaction component, we additionally conducted signal space projection (SSP) analysis (Tesche et al. 1995) in which MEG responses before subtraction were decomposed into visual and motor components. For the MEG responses under the passive viewing condition, SSP was conducted using only visual component. We found that the time course of visual component is very similar to that of RMS (Supplemental Fig. S2, C–F). The relation between peak latency/amplitude of SSP extracted visual response and peak MFR latency/amplitude is plotted in Supplemental Fig. S3. The correlation of amplitude and latency was $r = 0.63 (t_6 = 1.99, P = 0.09)$ and $r = 0.87 (t_6 = 4.30, P = 0.005)$ for the condition without reaching and $r = 0.61 (t_6 = 1.89, P = 0.1)$ and $r = 0.91 (t_6 = 5.41, P = 0.001)$ for the condition with reaching, which are a little bit lower than that between RMS and MFR.

To establish the correlation between MFR and MEG for a wide range of spatiotemporal frequency conditions, the second experiment measured the MFR and MEG for 15 spatiotemporal frequencies (0.05–1.6 c/deg, 2.5–10 Hz) with the stimulus contrast of 50%. The viewing condition was passive only because we didn’t find large differences between the passive viewing and the reaching conditions in the first experiment. Here we used RMS analysis rather than SSP analysis because MEG responses were recorded only under the condition without reaching. Figure 4 shows peak amplitude of the MFR and MEG as a function of spatial frequency, speed, and temporal frequency of gratings. Regression analysis indicated that, for both the MFR and MEG, the amplitude significantly decreases as the spatial frequency increases from 0.05 to 1.6 c/deg (99% confidence interval of regression slope is $-0.0057$ to $-0.0027$ for MFR and $-0.049$ to $-0.019$ for MEG), increases as the speed increases from 3.1 to 200 deg/s (regression slope is $0.027$ to $0.042$ for MEG), and increases as the temporal frequency increases from 2.5 to 10 Hz (regression slope is $0.007$ to $0.009$ for MFR, $0.057$ to $0.080$ for MEG). These tunings of the MFR are consistent with those in our previous report (Gomi et al. 2006). Figure 5 shows the peak latencies of the MFR and MEG. For both responses, the latency tends to increase for higher spatial frequencies (left).
although the effect was relatively small. Figure 6 directly compares the amplitude/latency of the MFR and MEG. Amplitudes were highly correlated with each other ($r = 0.85$, $t_{15} = 6.21$, $P < 0.001$). The higher correlation in comparison with the first experiment can be ascribed to the use of fixed contrast (50%) in the second experiment. Latencies also showed a trend for a positive correlation, but it was not significant ($r = 0.42$, $t_{15} = 1.79$, $P = 0.093$). The weaker correlation in comparison with the first experiment can be ascribed to the smaller variation in latency due to the use of single contrast and a limited range of spatiotemporal frequency in the second experiment (a larger latency change in the 1st experiment was given by the use of extremely low spatial frequency, 0.02 c/deg).

Figure 7 compares spatiotemporal tunings of the MFR and MEG. The dots represent the peak MFR and MEG amplitudes (mean over the subjects), and the plane surface was fitted to those data, respectively. The black and gray dots represent the data points over and underneath the fitting surface, respectively. The variance-accounted-for values in each fitting were 0.77 for the MFR and 0.91 for MEG, indicating that MFR and MEG increased with stimulus speed regardless of the stimulus spatiotemporal frequencies in the observed ranges.

**DISCUSSION**

The present study shows that large-field motion-evoked cortical responses measured by MEG have spatiotemporal tuning quite similar to that of a rapid involuntary manual response induced by the same visual motion (MFR). In addition, the peak latencies of the two kinds of responses were nearly the same and varied very similarly against variations in stimulus spatiotemporal frequency and contrast. Furthermore, in our recent observation (Gomi et al. 2007), the MFR and MEG variations for different sizes of grating motion were also correlated with each other.

**Compatible spatiotemporal tunings of MEG and MFR**

We found that the MEG response, as well as the MFR, increased as the spatial frequency was decreased and as the temporal frequency was increased. The spatiotemporal frequency specificity of MEG we observed here is qualitatively consistent with, but cannot be derived from the previous data reported by Anderson et al. (1996). The critical procedural difference between the two studies was that while Anderson...
et al. (1996) focused on the MEG responses to moving gratings of relatively high spatial frequencies (\( \approx 0.25 \) c/deg) presented within a small stimulus area (Gaussian envelope: sigma = 1.5 deg), we measured the MEG responses to moving gratings of a wider range of spatial frequency (including very low frequencies, \( \approx 0.02 \) c/deg) presented within a much larger stimulus area (35 deg in width). Our data show for the first time that the MEG response is considerably greater in the lower spatial frequency range (\( \approx 0.2 \) c/deg) than in the higher spatial frequency range (\( \approx 0.4 \) c/deg) and that the peak MEG amplitude increases as a function of grating speed with little dependency on spatiotemporal frequency. This speed-dependent tuning of MEG is consistent with a previous study using moving light spots (Kawakami et al. 2002). The spatiotemporal tuning we obtained is at least qualitatively consistent with those of the electroencephalographic response (Korth et al. 2000) and those of the blood-oxygen-level-dependent response in hMT+ (Singh et al. 2000). In addition, our data (experiment 1) show that when the temporal frequency is fixed at 10 Hz, the response amplitudes don’t show the monotonic increase with the decrease in spatial frequency (and thus the increase in speed), and peaks at the frequency of 0.05 c/deg.

We have shown in a previous study (Gomi et al. 2006) that the spatio-temporal tuning of the MFR resembles that of the ocular following response (OFR) (Miles et al. 1986). One might suspect that visual motion induces eye movements (OFR) and that eye-movement-related activity in hMT+ area may give rise to a pseudo-correlation between the MEG and MFR. However, we used a stimulus configuration that did not effectively induce the OFR (a grating with a horizontal blank band in the center). In fact, the iso-contour map of the MEG responses is mainly restricted to occipital areas (Supplemental Fig. S1) and did not indicate the induction of strong eye movements by the motion onset. The similarity of the OFR and MFR in spatiotemporal tuning supports the notion of correlation of MEG response with involuntarily motor responses in general.

With an increase in the grating contrast from 3 to 50%, a similar latency reduction obtained for both MFR and MEG. In contrast, peak amplitude enhancement was more prominent for MEG than for MFR. Note that the peak amplitude invariance of MFR to the contrast variation was also observed in Fig. 2D of Gomi et al. (2006) (for 2, 40, 70% contrast) although the

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**FIG. 5.** Variations in MFR and MEG peak latencies plotted as functions of spatial frequency (A and D), speed (B and E), and temporal frequency (C and F). The error bars represent SE.

**FIG. 6.** Comparisons of peak amplitudes (A) and peak latencies (B) between MFR and the MEG, measured with 15 spatio-temporal frequencies. The error bars represent SE. The correlation of the amplitudes was highly significant, while that of the latencies was marginally significant.
Dissimilarity between MFR/MEG and motion perception

The spatiotemporal tunings of MFR and MEG are significantly different from that of motion perception estimated from detection contrast sensitivity (Burr and Ross 1982; Gomi et al. 2006), which has a peak at a higher spatial frequency and at a lower temporal frequency. We take this dissociation as support of the idea that motion-evoked cortical response measured by MEG is correlated with involuntary motor responses, much more than it is so with conscious motion perception. It is, however, suggested that sensitivity for detecting motion, the standard measure of the sensitivity of visual motion perception, mainly reflects the property of an early motion processing stage (Morrone et al. 1995), and the spatial frequency tunings of later stages are not well characterized. Future studies need to address what the spatio-temporal tuning of suprathreshold motion perception is like and how it is related to the tunings of MFR and MEG.

We found that the peak latency of MEG response evoked by an onset of a grating motion was 120–200 ms. This is comparable to the MEG latency for transition to coherent global-dot motion from incoherent motion (150–300 ms) (Amano et al. 2006; Lam et al. 2000). On the other hand, the latency of voluntary behavioral response to the perception of stimulus onset, which presumably reflects the time to reach perceptual decision, is 300–600 ms (Amano et al. 2006). Although the absolute difference in latency may be partially ascribed to the time for the postperceptual process included in the behavioral reaction time, the variations in the onset latency of MEG response (including those related with stimulus strength change and response change) are, though correlated, too small to account for the variations in behavioral reaction time (Amano et al. 2006). A model that can successfully link the MEG response to the speed course and the behavioral latency assumes temporal integration of motion-evoked MEG signals, which arguably corresponds to temporal integration of hMT+ signals in the subsequent processing stages (Amano et al. 2006; Cook and Maunsell 2002; Shadlen and Newsome 2001). This suggests that the macroscopic cortical response evoked by visual motion, at least that measurable by MEG, reflects an intermediate stage of motion perception. That is, although the MEG response has, in part, a correlation with final perceptual decisions, it may not directly reflect the cortical activity responsible for the perceptual decisions.

Neuronal responses underlying the speed-dependent MEG response

Due to our limited success of source localization from the MEG response, we cannot definitely conclude which brain areas are responsible for the observed MEG responses, but the activities in occipital and tempo-occipital areas indicated by the iso-contour maps of the majority of subject suggest that the observed MEG responses are likely to reflect the population activity of the neural circuit for visual motion processing in the areas including V1, V2, and hMT+. It is worth mentioning that the spatiotemporal frequency tuning of the peak response observed in this study was similar to that of the cortical activities localized at hMT+ in previous studies (Anderson et al. 1996; Singh et al. 2000), while different from those localized at V1/V2 (Singh et al. 2000).

In MT, as well as in V1 and V2, motion-related information is considered to be represented in the activation pattern of a population of neurons having a diversity of stimulus tunings and to be decoded and utilized in the subsequent neural stages. Previous studies have suggested that the perceived speed may be encoded in the form of the ratio (Thompson 1984; Smith 1985) or vector average (Lisberger and Movshon 1999; Pribe and Lisberger 2004; but see also Krekelberg et al. 2006) of MT neurons with various speed tunings. On the other hand, MEG signals are likely to reflect the total sum of postsynaptic potential of all the neurons in the cortical region of interest. Such a gross measure of cortical activity does not necessarily reflect the contents of information for perception represented by the neurons. Given the direct correlation of the gross cortical activity to visual motion (revealed by MEG) with MFR, we speculate that the reflective visuo-motor system...
might be driven directly by a simple summation of the activity of motion processing areas. This simple structure would be advantageous for quickly generating motor responses. Given the monotonic increase of MEG with stimulus speed, we further speculate that the spatiotemporal tuning of gross activity of neural processing for sudden visual motion may be optimized to generate appropriate quick motor responses.

The spatiotemporal tuning of MEG response agrees well with high-speed preference of monkey MST neurons (Duffy and Wurtz 1997; Kawano et al. 1994) but not with mid-speed preference of the majority of MT neurons (Cheng et al. 1994; Lagae et al. 1993; Liu and Newsome 2003; Maunsell and van Essen 1983; Perrone and Thiele 2001; Pribe et al. 2003) nor with even slower speed preference of V1/V2 neurons (Foster et al. 1985). There are several mutually nonexclusive possibilities to account for this apparent discrepancy between MEG and electrophysiology. First, MEG might be somehow more sensitive to the activity of MST, or that of other high-speed preference areas, than MT activity. Second, MEG might be more sensitive to the cortical activity evoked by high-speed motion than that evoked by low-speed motion due to the difference in, say, synchronization of neuronal activities. Third, our use of very low spatial frequencies and/or a very large visual field, which had been rarely used in previous electrophysiological studies, might have highlighted the neural activity for very high speeds that had been otherwise underestimated. Fourth, there might be some mechanisms that make the tuning of population response significantly different from that expected from the population distribution of preferred speed of single neurons, such as asymmetric speed tuning and speed-dependent activity level difference. All these arguments remain highly speculative, however, and further physiological study is necessary to reveal how the monotonically increasing speed tuning of MEG is related to neuronal activities in V1, V2, MT, and MST.

Neuronal responses generating MFR

If the observed MEG response contributes to the MFR generation, the MEG response should precede the MFR to satisfy the causality. As far as peak latency is concerned, the MEG responses were not fast enough to support a sequential propagation from the visual response to the acceleration response of the hand as shown in Fig. 3. Response peak comparison, however, might not be appropriate for examining the causality because several factors of the complex response organization process could affect the peak latency for both the MEG and MFR. Although the onset latencies might be more suitable for the discussion of causality, it was hard to compare them too, because of the difficulty in accurately specifying the MFR onset latency for each stimulus condition from the current observations due to the signal bias and noises. To further examine the causality, electrophysiological stimulation, such as transcranial magnetic stimulation (TMS) or electrical stimulation, will be required. Even though we cannot rigorously prove the causality, we can at least conclude that a common visual motion analysis (cortical and/or subcortical) contributes to the MEG response and MFR, providing the unique specificity of the stimulus spatiotemporal frequency.

Theoretically, MEG responses to moving gratings measured during reaching, in which MFR was evoked, would contain the responses related to the motor response as well as those evoked by visual motion. Because our previous TMS study suggests that the primary motor area (M1) is involved in MFR generation (Kimura et al. 2005), we expected to find MEG responses originating from M1. However, when the MEG measured during hand movement with a stationary stimulus was subtracted from that with moving gratings, the subtracted MEG was quite similar to the MEG measured under passive viewing condition with the same moving gratings. In other words, we didn’t find the MEG responses reflecting the activity of motor neurons related to the MFR. This might be because the MFR is a modulation of motor response, which is relatively smaller than the responses of motor neurons generating reaching movement itself. To further investigate the brain areas involved in the MFR, fMRI study will be necessary.

GRANTS

This work was supported by Japan Society for the Promotion of Science Grant to K.Amano.

REFERENCES


