Approach of visual stimuli facilitates the prediction of tactile events and suppresses beta band oscillations around the primary somatosensory area

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The purpose of the present study was to investigate whether the approach of visual stimuli influences prediction of subsequent tactile events. For this purpose, we examined electroencephalograms (EEGs) during the prediction of tactile events when visual stimuli did or did not approach. Tactile stimuli were presented with a high probability (80%) of being applied to the left (or right) index finger and a low probability (20%) of being applied to the opposite index finger. In the approach condition, visual stimuli were presented towards the hand to which the high-probability tactile stimuli were presented; in the neutral condition, visual stimuli did not approach. The result of time-frequency analysis for the EEGs showed that beta band event-related spectral perturbation at the electrodes around the primary somatosensory area (C3 and C4) was suppressed about 300 ms before the presentation of a tactile stimulus and that event-related desynchronization (ERD) occurred in all conditions. Moreover, the beta band ERD of the approach condition was larger than that of the neutral condition. These results provide evidence that the approach of visual stimuli facilitates prediction itself for subsequent tactile events.
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Introduction

Prediction is one of the main cognitive functions of the brain. We adapt to the environment by predicting an event, detecting prediction error as a gap between the prediction and the event, and correcting the prediction (for a review, see [1]). In particular, predicting a tactile event before physical contact occurs is necessary for us to defend ourselves. Recent studies reported that prior visual stimuli approaching the body facilitate prediction of a subsequent tactile event [2–4]. In these studies, the prediction of a tactile event was facilitated by visual stimuli approaching the body; as a result, tactile events that deviated from this prediction elicited large amplitudes of event-related brain responses (ERPs). In other words, these studies focused on prediction error. The detection of prediction error is important for correcting predictions; similarly, prediction itself is also important for defending the body. However, it remains unclear whether approaching visual stimuli influence the occurrence of prediction itself for subsequent tactile events.

Previous prediction studies reported that neuronal oscillations at each sensory cortex decrease during the prediction of each sensory event [5] for a review, see [6–7]. This phenomenon is called event-related desynchronization (ERD); in particular, ERD for a tactile event occurs in the beta band (14–30 Hz) during prediction of the event about 300 ms before the event occurs [8]. Therefore, it seems likely that this ERD in the beta band before the tactile event will occur if the approach of visual stimuli influences prediction itself for subsequent tactile events.

The purpose of the present study was to investigate whether the approach of visual stimuli influences prediction itself for subsequent tactile events. For this purpose, we examined electroencephalograms (EEGs) during the prediction of tactile events when visual stimuli did or did not approach. Participants were asked to perform a simple reaction time task to tactile stimuli, which were presented after the presentation of visual stimuli. Tactile stimuli were presented with a high probability (80%) of being applied to the left (or right) index finger and a low probability (20%) of being applied to the opposite index finger. In the approach condition, visual stimuli were presented towards the hand to which the high-probability tactile stimuli were presented; in the neutral condition, visual stimuli did not approach. The frequency with which the tactile stimuli would be presented to each index finger was told to participants before the experiment. Therefore, the conditions differed only in the presentation of visual stimuli; participants could predict the location of a high-probability tactile stimulus regardless of the approach of visual stimuli. We predicted that

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ERDs in the beta band would occur in each condition before the presentation of the tactile stimulus if participants can predict the tactile stimulus [8], and that the ERD in the approach condition would be larger than that in the neutral condition if the approach of visual stimuli facilitates prediction itself for a subsequent tactile stimulus. In addition, as in a previous study [2], we examined contingent negative variation (CNV) [9] before the presentation of tactile stimuli to ensure that temporal prediction of tactile stimuli did not differ between conditions. We predicted that the amplitude of CNV would not differ between conditions if participants can predict the timing of the presentation of the tactile stimulus in both conditions.

Methods

Participants

Eighteen undergraduate and graduate students (10 females and 8 males; 18–25 years of age) participated in the experiment. All participants were right-handed, according to their self-report, and had normal or corrected-to-normal vision. This experiment was approved by The Institute of Scientific and Industrial Research's Research Ethics Review Board under Osaka University regulations. Written informed consent was obtained from all participants, and their rights as experimental subjects were protected.

Stimuli and procedure

The stimuli and procedure were set according to a previous study [2]. In the experimental room, participants were seated and put their hands and forearms on an obliquely oriented board in front of them. Their hands were 32.0 cm apart. Tactile stimuli were presented to participants' index fingers by a vibration stimulus generator and a solenoid vibrator (Uchida Denshi Corporation, FB-2006D and FB-1005). The vibration was 250 Hz of 200 ms in duration. These stimuli were presented to the left (or right) index finger with a high probability (80%), and to the opposite index finger with a low probability (20%). These stimuli were presented in random order from trial to trial, and the order of the location (left or right) of the stimulus presentation at high (or low) probability was counterbalanced across blocks.

Three white light-emitting diodes (LEDs) were used as visual stimuli. Each LED was a square with 0.8 cm sides. Three LEDs were placed at equal distances (8.0 cm intervals) between the arms on an obliquely oriented board. The visual stimuli were single block pulses of 25 cd and 200 ms duration.

Each trial was composed of three visual stimuli and one tactile stimulus. The stimulus onset asynchrony was set to 1000 ms. The interval between trials was either 1000 or 1200 ms at random with equal probability. Each block was composed of 84 trials [high-probability tactile stimuli: 64 trials; low-probability tactile stimuli: 16 trials; no tactile stimuli (catch trial): four trials], which took approximately 7 min. Two blocks were presented for each condition. The interval between blocks was 2 min, and after the second block, the participants rested for 10 min and then started the remaining two blocks. The order of conditions was randomized between participants.

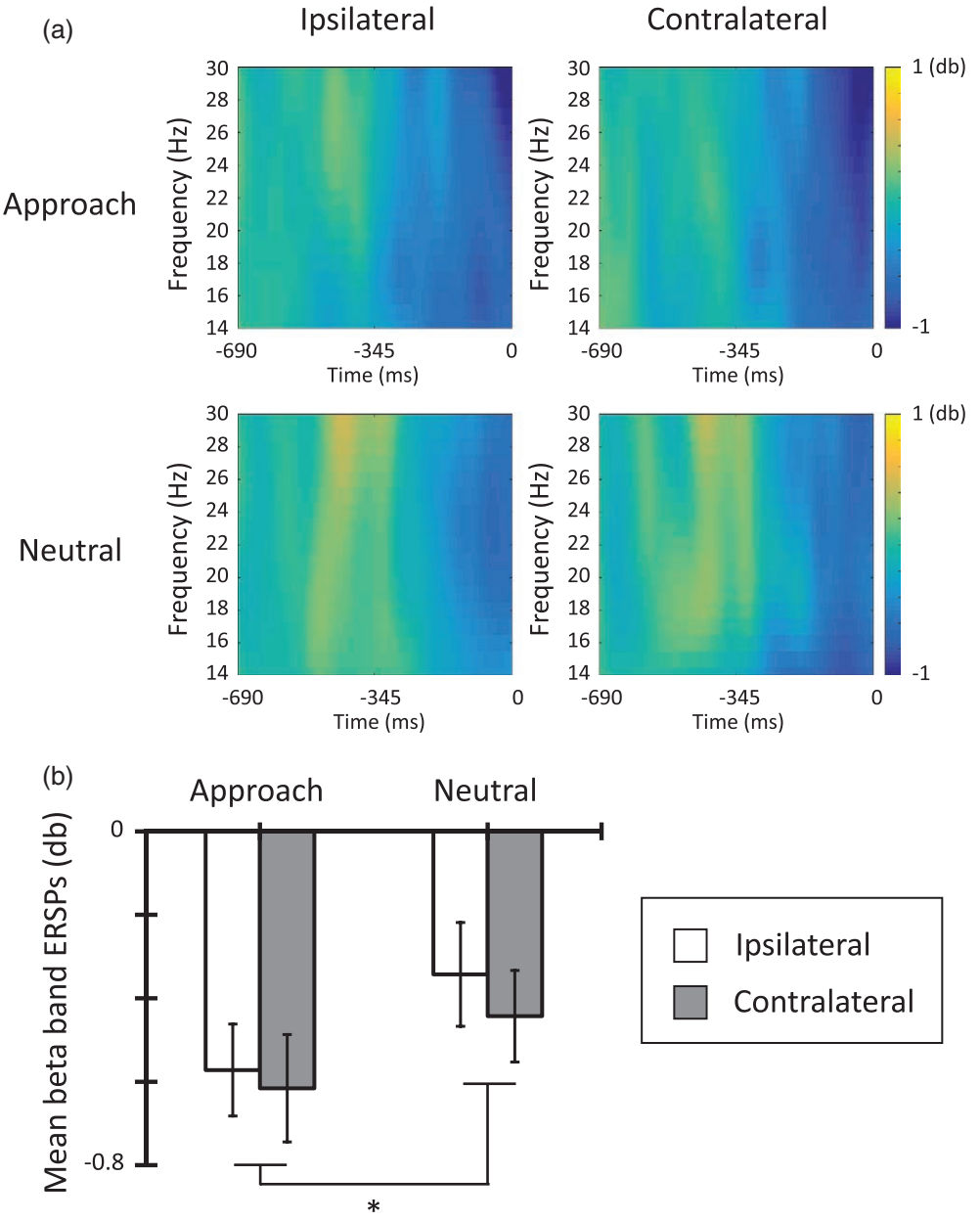
The two conditions were distinguished by the pattern of visual stimuli, and the patterns were administered in separate blocks. In the approach condition, LEDs flashed sequentially towards the hand where the high-probability tactile stimulus was presented (i.e., if the high-probability tactile stimulus was set at the left index finger, the LEDs flashed sequentially right, center, and left), and the subsequent tactile stimulus was presented to the left (or right) index finger. In the neutral condition, the center LED flashed three times with the same timing, and then the subsequent tactile stimulus was presented to the left (or right) index finger. The participants were required to gaze at the center LED, in order to control their eye movements, and not to move their eyes and bodies more than necessary in each condition. Moreover, the participants were instructed to respond by pressing a button with the left (or right) foot whenever the tactile stimuli were presented, and to not respond when tactile stimuli were not presented (i.e., the catch trials). Half of the participants used the left foot and the other half used the right foot. Finally, they were told at the start of each block which hand would be presented with the high-(low-) probability stimuli.

Recording and analyses

EEG data were recorded by Polymate AP1132 (Miyuki Giken, Japan) and an electrode cap (Easycap GmbH, Germany) using Ag/AgCl electrodes at 26 sites (Fp1, Fp2, F7, F3, Fz, F4, F8, FC3, FCz, FC4, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, Oz, O2) according to the modified 10–20 System. In addition, electrodes were also placed on both earlobes (A1 and A2). The reference electrode was on the tip of the nose, and the ground electrode site was AFz. The data from all channels were recorded using the Mobile Acquisition Monitor Program (Miyuki Giken, Japan). The electrode impedances were kept below 10 kΩ. A DC filter was used at recording. The sampling rate was 1000 Hz.

To analyze the EEG data, the EEGLAB toolbox [10] and ERPLAB toolbox [11] on MATLAB (Mathworks Inc.) were used. Artifacts derived from eye movements and eye blinks were rejected using an automatic EEG artifact detector based on the joint use of spatial and temporal features (ADJUST) of the EEGLAB toolbox [12]. In the time-frequency analysis, the EEG data epoch was 1800 ms (including a 900 ms prestimulus of the third visual stimulus). Epochs in which the EEG signal variation exceeded ±100 μV were rejected. After artifact rejection, EEG data were transformed by the Morlet wavelet transformation function applied in a Hanning-tapered window in EEGLAB. The settings were as follows: epoch time limits: –900 to 900 ms,

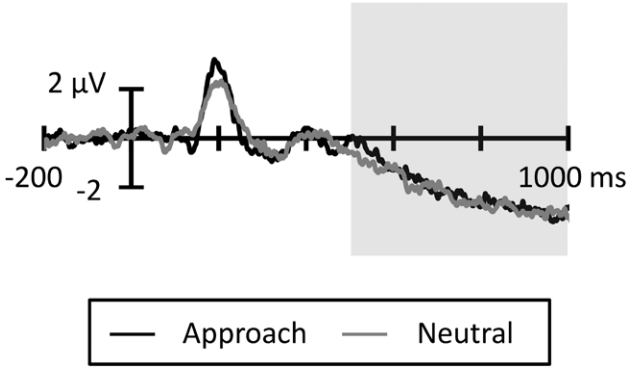
Fig. 1



(a) The beta band event-related spectral perturbations (ERSPs) in each condition and each laterality, and (b) the mean beta band ERSPs at the time range of −300 to 0 ms in both conditions. The error bars indicate the standard errors (SEs) of the means across participants. An asterisk indicates a significant difference in the mean beta band ERSPs between conditions (*$P < 0.05$).

using 400 time points; frequency limits: 8–30 Hz; baseline limits: −900 to −500 ms; wavelet cycles: 3–0.5. The processed data was output from −691.88 to 690.88 ms (400 time points) and from 8 to 30 Hz (22 frequency points). The beta band (14.29–30 Hz) ERSPs for time range 300–0 ms at the electrodes of C3 and C4 (i.e., the neighboring electrodes for the primary somatosensory area) were averaged in each block, consistent with a previous study [8]. In addition, these electrodes were distinguished by prediction of a tactile stimulus. C3 (C4) is ipsilateral and C4 (C3) is contralateral when the block with the high-probability tactile stimulus is presented to the left (right) hand. The averaged beta band ERSP for ipsilateral and contralateral were calculated in each condition. After this processing, the numbers of the remaining trials were 155–160 (0–3.1% rejected) for the approach condition and 157–160 (0–1.9% rejected) for the neutral condition.

Fig. 2



Grand average related brain response (ERP) waveforms for each condition at the Cz electrode sites. The gray area denotes the time range of contingent negative variation (CNV) (500–1000 ms).

To extract CNV, the EEG data were digitally band-pass filtered at 0.01–30 Hz (6 dB/octave) using an IIR Butterworth analog simulation filter. After this, the data epoch was 1200 ms (the baseline was a 200–0 ms prestimulus of the third visual stimulus, and the onset of the tactile stimulus occurred at 1000 ms). Epochs in which the EEG signal variation exceeded ±100 μV were rejected. After artifact rejection, the numbers of remaining trials were 151–160 (0–5.6% rejected). The mean CNV amplitude was obtained from a latency window of 500–1000 ms. The appropriate latency window was defined based on observation of the resultant ERP waveforms.

Two-way repeated measures analysis of variance (ANOVA) of reaction times in response to the tactile stimuli were conducted with the two conditions (approach condition and neutral condition) × two stimulus probabilities [high probability (80%) and low probability (20%)]. To check the ERD, one-sample *t*-test of beta band ERSPs were conducted with all combinations between conditions and lateralities (ipsilateral and contralateral). If ERD occurred in all combinations, two-way repeated measures ANOVAs of ERSPs were conducted with the two conditions × two lateralities. These ANOVAs were conducted by applying Greenhouse-Geisser corrections to the degrees of freedom [13] when Mauchly's sphericity test was significant. The effect sizes have been indicated in terms of partial eta squared (η^2p). Post hoc comparisons were made using Shaffer's modified sequentially rejective multiple test procedure, which extends Bonferroni *t*-tests in a stepwise fashion [14]. In addition, the mean CNV amplitudes at Cz, where the CNV was elicited at maximum amplitude, were compared between conditions by a paired *t*-test. The effect size was calculated by computing Cohen's *d* [15]. The significance level was set at $P < 0.05$ for all statistical analyses.

Results

Behavioral data

Averaged reaction times of all participants were 426 ms (SE = 15.13), 444 ms (SE = 15.41), 419 ms (SE = 13.89), and 428 ms (SE = 17.57) for the approach-high-probability, approach-low-probability, neutral-high-probability, and neutral-low-probability stimuli. The results of the ANOVAs revealed that the main effect of stimulus probabilities was significant [$F(1, 17) = 20.70$, $P < 0.001$, η^2p = 0.55], and the reaction time to the low-probability stimulus was longer than the reaction time to the high-probability stimulus. The main effect of conditions [$F(1, 17) = 3.11$, $P = 0.10$, η^2p = 0.15] and the interaction [$F(1, 17) = 1.99$, $P = 0.18$, η^2p = 0.10] were NS.

Beta band event-related spectral perturbations

Figure 1 illustrates (a) the beta band ERSPs in each condition and each laterality and (b) the averaged beta band ERSPs at the time range of –300 to 0 ms in all conditions and lateralities. The results of the one sample *t*-test revealed that the beta band ERSPs were smaller than zero in all conditions and lateralities [*t*s(17) > 2.76, *P*s < 0.01, *d*s > 0.92); therefore, ERD occurred in all conditions and lateralities. The results of the ANOVAs revealed that the main effect of conditions was significant [$F(1, 17) = 6.48$, $P = 0.02$, η^2p = 0.28], and that the ERD of the approach condition was larger than that of the neutral condition. The main effect of laterality [$F(1, 17) = 3.57$, $P = 0.08$, η^2p = 0.17] and the interaction [$F(1, 17) = 1.04$, $P = 0.32$, η^2p = 0.06] were NS.

Contingent negative variation

Figure 2 illustrates the grand average CNV elicited in all trials at Cz, where the CNV was elicited at maximum amplitude. The gray area indicates the time range of CNV (500–1000 ms). Comparisons between conditions by paired *t*-tests of mean amplitude of CNV revealed no significant difference [$t(17) = 0.30$, $P = 0.57$, $d = 0.08$].

Discussion

The present study aimed to investigate whether the approach of visual stimuli influences prediction itself for subsequent tactile events. For this purpose, ERDs in the beta band, reaction times, and CNVs were compared between the approach condition and the neutral condition. Our results showed that the amplitude of CNV did not differ between the conditions and that the reaction time to the low-probability stimulus was longer than the reaction time to the high-probability stimulus. These results are the same as in a previous study [2] and indicate that the participants could predict the timing of the presentation of the tactile stimulus and the location of the presentation of the high-probability tactile stimulus in both conditions.

Moreover, the beta band ERSPs were suppressed about 300 ms before the presentation of the tactile stimulus in

all conditions and lateralities; that is, ERD occurred in all conditions and lateralities. This ERD occurs during prediction of a subsequent tactile event [8]. Taken together, the results of the reaction times, CNVs, and ERDs show that the participants could predict the presentation of the subsequent tactile stimulus. Furthermore, the beta band ERD of the approach condition was larger than that of the neutral condition. The ERD before the presentation of a stimulus reflects the intensity of the prediction of a subsequent stimulus [5–8]. The only difference between conditions was the presentation of visual stimuli. Therefore, this result suggests that the approach of visual stimuli facilitates prediction itself for a subsequent tactile stimulus.

This prediction effect is considered to be based on the mechanism of multimodal integration between visual and tactile modalities. Previous studies reported that many brain regions are involved in integrating visual and tactile information [16]. In particular, the premotor region is related to the processing of multiple sensory stimuli and also responds to visual stimuli appearing in the peripersonal space [17]. Visual stimuli appearing in the peripersonal space function as predictive activation for a tactile stimulus, and this information and the processing of each visual and tactile stimulus are integrated in the ventral interparietal area [18–20] for a review, see [21]. Based on these previous studies, our results can be interpreted to mean that visual stimuli which approached the peripersonal space activated these intercortical networks and facilitated the prediction of the subsequent tactile stimulus.

Previous studies reported that the ERDs at the contralateral region were larger than those of the ipsilateral region [5–8]; however, this laterality effect did not occur in our results. As with our results, the previous studies of tactile prediction reported that this laterality effect did not occur when the number of trials was small [22] and at the beginning of the experiment [23]. This result has been explained as the result of gradual processing of the repetitive presentation of a stimulus [23]. In fact, this laterality effect occurred when the number of trials was larger than the number in our study [8,23]. Therefore, it is possible that ERD for prediction is influenced by the number of trials; further investigation is necessary.

In summary, the present study indicated that the approach of visual stimuli influences not only prediction error but also prediction itself for a subsequent tactile stimulus. This result suggests that the approach of visual stimuli is important information for prediction of subsequent tactile events and that it influences a gradual tactile prediction process. This study extended our understanding of the predictive function based on multisensory interaction.

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Conflicts of interest

There are no conflicts of interest.

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