

Haptic localizations for onset and offset of vibro-tactile stimuli are dissociated

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Abstract When humans explore the external world, hand and arm movements play important roles. Spatio-temporal arrangements of the environment are perceptually generated mainly by means of the sensory–motor integration of the internal model of these movements with the information obtained during the movements. In order to investigate the mechanisms of this integration process, localization tasks have been studied, and previous studies have suggested that the integration process does not work properly around the time of a hand movement. In particular, when a transient vibro-tactile stimulation is presented before, during, or after a hand movement, the stimulus is systematically mislocalized. However, it is debatable whether the tendency to mislocalize a transient stimulus indicates a general failure of the sensory-motor integration process. Here we investigated the generality of the tendency towards mislocalization

by observing haptic localizations to different target types, the onset and offset of continuous vibro-tactile stimuli. We found similar types of mislocalizations in responses to the transient vibration and the onset of a continuous vibration, and a clear difference in the types of mislocalizations in responses to the onset and offset of continuous vibrations.

Keywords Haptic localization · Hand movement · Internal representation · Sensory–motor system · Vibro-tactile stimulation

Introduction

Humans move the hand, a sensitive and active probe, for perceiving spatio-temporal arrangements in a dynamic environment. When the hand is moved from one position to another and makes contact with an object during the movement, humans can localize the contact position even without visual guidance. This is because the sensory–motor system can integrate the internal hand movement information with the temporal information about the contact from the periphery. The internal representation of the arm and hand is fundamental for accurate motor movements and spatial cognition (Paillard and Brouchon 1968; Horch et al. 1975; Sittig et al. 1987; Cordo 1990; Cordo et al. 1994; Krakauer et al. 1999; Haggard et al. 2000). Internal models of hand movements, mainly forward models, have been intensively studied (Kawato et al. 1987; Wolpert et al. 1995; Flanagan and Lolley 2001; Johnson et al. 2002).

Spatial localization tasks and temporal order judgment tasks are effective techniques for investigating how the internal representation of the movement and the information obtained during the movement are integrated in the brain (McCloskey et al. 1983; Jirsa et al. 1992; Dassonville

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1995; Azuma and Haggard 1999; Nijhawan and Kirschfeld 2003). In such tasks, a visual, auditory, or vibro-tactile stimulus is presented around the time of a hand movement, and participants are asked to point out the stimulated position or compare the stimulation timing with the timing of the hand movement. These previous reports indicated that the sensory–motor integration does not work perfectly. In particular, when a transient vibro-tactile stimulation was presented before, during, or after the hand movement, the stimulus was systematically mislocalized (Dassonville 1995). The participants localized the stimulus toward the direction of the hand movement around the time when the movement began, even when the stimulus was presented before the hand movement.

However, it is debatable whether the errors in localization to a transient stimulation suggest a general failure of the sensory–motor integration process. Specific effect arising from the transient stimulus itself may contribute to the localization errors. Typical environments exhibit a high degree of spatio-temporal coherence, and the localization to continuous stimuli may tend to differ, as observed in visual localization at the time of oculo-motor movement (See Cai et al. 1997; van Beers et al. 2001; Watanabe et al. 2005). Here we investigated the generality of the mislocalization tendency by observing haptic localizations in response to different target types. In our experiments, the onset timing, the offset timing, and the duration of the vibration were systematically varied. We asked participants to manually point to the perceived position of the onset or offset of a presented vibration. In the first experiment, the time course of the localization to a transient vibration was measured, and the measured time course served as the basis for comparing the data with subsequent experiments. In the second and third experiments, a continuous vibration was presented until long after, or from long before the hand movement, and the onset or offset of the vibration was varied. The participants localized the onset or offset of the continuous vibration.

Materials and methods

Participants

Four right-handed participants (three naive males, and one male author), aged from 22 to 26 years, performed all experiments.

Apparatus

A small disk-shaped vibrating motor (NEC TOKIN Corporation, Miyagi, Japan, TYPE33) was mounted on the nail of the right index finger of the participant with double-sided sticky

tape. The vibration motor was 16 mm in diameter, 4 mm in width, and 4 g in weight, and the vibration frequency was 130 Hz. The participant was instructed to make a rapid rightward hand movement with the right arm along an aluminum bar, as shown in Fig. 1a. The motor was activated at around the time of the hand movement. A thin electric wire that connected the motor to a microcomputer (Microchip Technology Inc., Arizona, USA, PIC18F452), which controlled the motor. The position of the index finger was measured using a laser displacement sensor (KEYENCE, Osaka, Japan, LK-500). The sampling rate of the sensor was 1,024 samples per second. Data from the microcomputer and the laser displacement sensor were collected in a PC using a data logger (KEYENCE, Osaka, Japan, NR-2000) after irrelevant noise had been removed from the data by a low-pass filter (cut-off frequency, 2.5 kHz). The sampling rate of the logger was 1,000 samples per second. The timings of the vibration and time course of finger movement were recorded together.

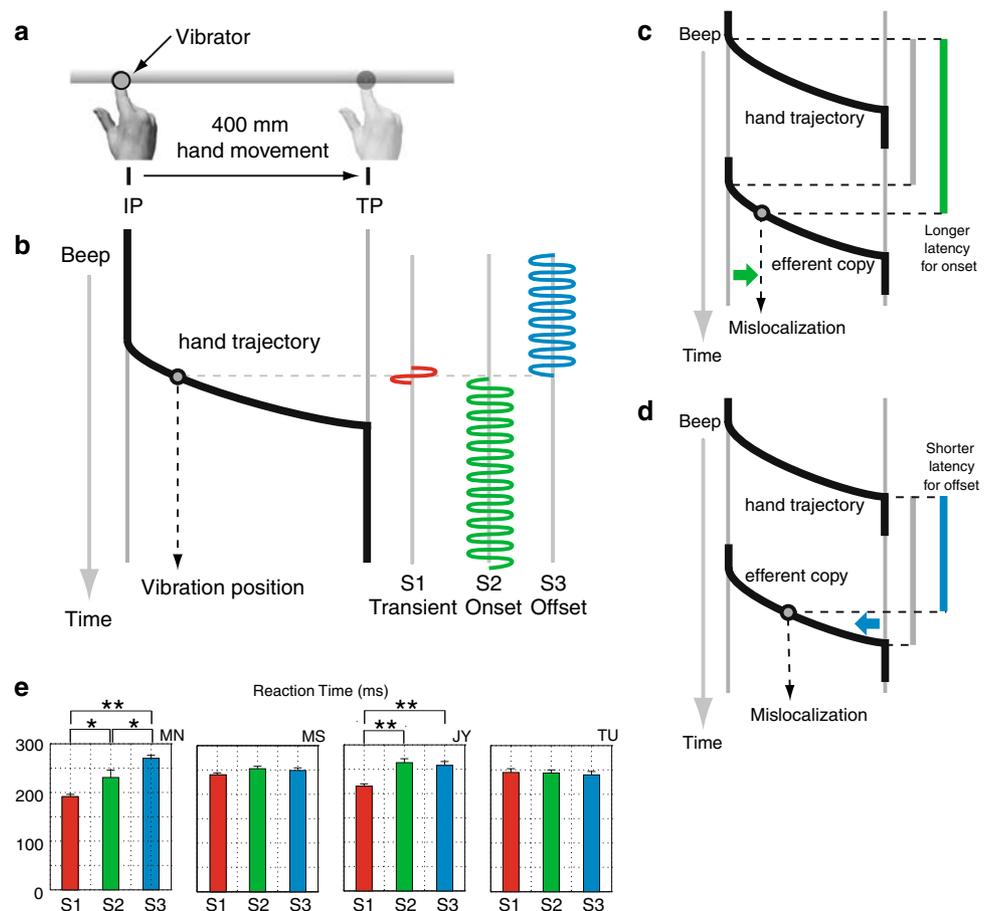
Procedure

A participant sat with his right index finger on a thin aluminum bar. At the beginning of each trial, an audio signal (100 Hz) was presented, and the participant immediately made a rightward hand movement along the bar. A vibro-tactile stimulus was presented before, during, or after the hand movement. After the hand movement, the participant manually pointed to the stimulus location with their right index finger. When the location had been decided, they pushed a button with their left finger to record the indicated location and then placed their right index finger at the initial position on the aluminum bar (The initial position was marked with sticky tape). When they were ready, they pushed the button again, and the next trial began.

Participants performed all experiments with their eyes closed, and the vibration was inaudible, so that they could only perform the localization using internal sensory–motor information. The trip length and duration of the hand movement were about 400 mm and 300 ms, respectively. The participants practiced performing the appropriate hand movement (with a clear start and termination and with stable length and duration) before the experiments.

We used three types of vibro-tactile stimuli. Figure 1b shows the timings of these stimuli. In the first condition (S1), the duration of the stimulus was 20 ms, which was similar to the duration of the transient vibration used by Dassonville (1995). This vibration duration was sufficient for detecting the stimulus, even during hand movement. In the second condition (S2), the vibration began around the time of the hand movement and continued for about 1 s after it. The participants indicated the onset position of the continuous vibration. In the third condition (S3), the vibration started long before the hand movement initiation

Fig. 1 **a** Experimental configuration. **b** Timing charts of presented vibro-tactile stimuli. **c** When the latency for the onset is longer than that of the efferent copy, a mislocalization toward the hand movement can be observed before the hand movement. **d** When the latency for the offset is shorter than that of the efferent copy, a mislocalization in the direction opposite to the hand movement can be observed around the end of the hand movement. **e** Reaction times in response to the transient vibration (*left*), vibration onset (*center*), and vibration offset (*right*) in milliseconds. The vibrations were presented to the nail of the right index fingers with the hands static. Then, the participants immediately pushed the button with their left index fingers. The averages and standard errors for 60 trials are shown. (* $p < 0.05$, ** $p < 0.01$)



(about 2–4 s before, randomized) and ceased around the time of the hand movement. The offset position of the vibration was localized.

The total number of trials for each stimulus condition was 240, divided into eight blocks of 30 trials (8×30). The order of the stimulus conditions was randomized between blocks, and the same type of stimulus was presented in a block.

Data analysis

We excluded trials in which the participants moved their finger over too short or long a distance (shorter than 350 mm or longer than 450 mm), for too short or long a duration (shorter than 200 ms or longer than 400 ms), or for early or late latency (shorter than 200 ms or longer than 500 ms). The start and end times of hand movement were defined as time that hand movement speed exceeded and became lower than 500 mm/s, respectively.

Results

All results in the three stimulus conditions are shown in Figs. 2 and 3. The same data are plotted with regards to

absolute reported position in Fig. 2 and localization error in Fig. 3. The individual data points for each participant (MN, MS, JY, TU) are shown in Figs. 2a–c and 3a–c. Averages across the four participants are shown in Figs. 2d and 3d. The horizontal axis represents the time difference from the initiation of the hand movement to the time the onset (Figs. 2a, b, 3a, b) or offset (Figs. 2c, 3c) of the vibro-tactile stimulus was presented in milliseconds. A negative value means that the stimulus was presented before the hand movement. The yellow areas (0–300 ms on the horizontal axis) indicate the time range of the hand movement. The vertical axes represent the reported absolute position in Fig. 2 and amount of localization error in Fig. 3 in millimeters.

The results of transient vibration localizations (S1) are shown in the first column from the left (Figs. 2a, 3a). Mislocalizations toward hand movement were observed in the data for all participants. The mislocalizations initiated about 100 ms before the hand movement and continued until the end of the hand movement. The amount of mislocalization was maximized in the early time range of the hand movement (around 0–100 ms). These results are consistent with those reported by Dassonville (1995), although the amount of mislocalization was smaller than in

Fig. 2 Localization results. *Horizontal and vertical axes* represent the time to hand movement initiation in milliseconds and the reported location in absolute coordinate in millimeters, respectively. **a** Transient vibration condition (S1). **b** Vibration onset condition (S2). **c** Vibration offset condition (S3). Results of all valid trials and curves and data points that show the averages of the data in 100-ms bins are shown. The *solid curve* denotes the mean time course of the hand movement. The numbers of valid trials, obtained after the data analysis, are shown in the figures. **d** Curves and data points that average the data in the 100-ms bins across the four participants. The individual data were normalized to the standard amplitude (400 mm) before averaging. *Red circles, green triangles, and blue crosses* represent the averaged data for transient vibration, vibration onset, and vibration offset, respectively

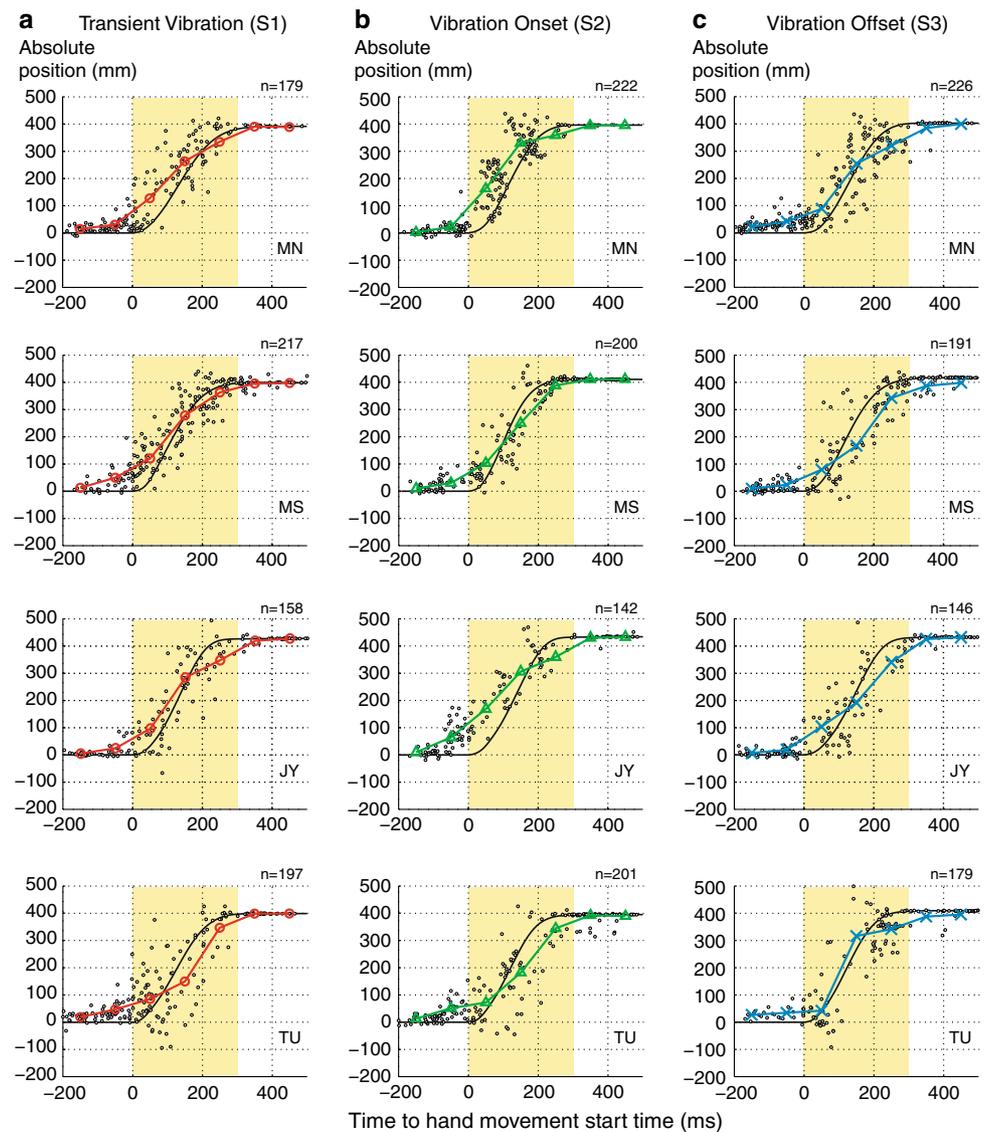
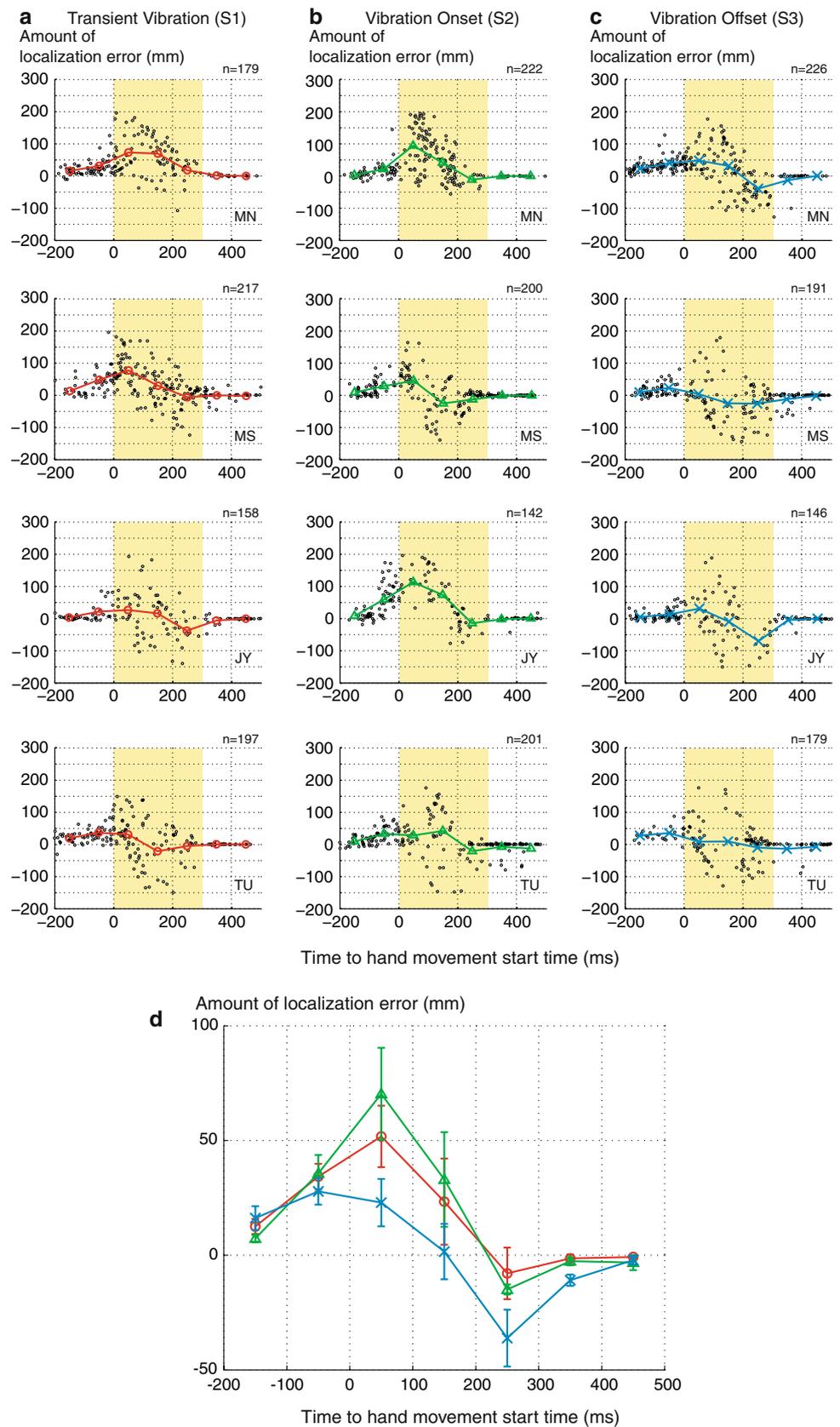


Fig. 3 Localization results represented as amount of error. *Horizontal and vertical axes* represent the time to hand movement initiation in milliseconds and the amount of localization error in millimeters, respectively. **a** Transient vibration condition (S1). **b** Vibration onset condition (S2). **c** Vibration offset condition (S3). Results of all valid trials and curves and data points that show the averages of the data in 100-ms bins are shown. **d** Curves and data points that average the data in the 100-ms bins across the four participants. *Error bars* indicate the standard errors. The individual data were normalized to the standard amplitude (400 mm) before averaging. *Red circles, green triangles, and blue crosses* represent the averaged data for transient vibration, vibration onset, and vibration offset, respectively



Dassonville's experiments, in which the hand traveled a longer distance (520 mm) than in our experiment (400 mm).

The results of onset localizations (S2) are shown in the second column from the left (Figs. 2b, 3b). Generally, the errors in localization to the onsets of the continuous vibrotactile stimuli showed the same tendency as those in localization to the transient vibrations. Errors in the same direction as the hand movement started around 100 ms before the hand movement and continued until the end of the hand movement. The maximum magnitudes of mislocalizations were comparable to or larger than those to the transient vibration in the data for all participants.

The results of offset localizations (S3) are shown in the third column from the left (Figs. 2c, 3c). Although the data were more scattered and the magnitude of the localization error was smaller than in the other conditions, these errors showed a different tendency from those in the previous two conditions. Specifically, in addition to the mislocalizations toward the direction of the hand movement observed in the early range of the hand movement, the mislocalizations in the opposite direction were observed in the later range of the hand movement.

The averaged data across the four participants (Figs. 2d, 3d) clearly demonstrate the difference in the localizations to the onset and offset of vibrations. The curve of offset localization always falls below the other curves in absolute reported position (Fig. 2d), and widely diverges from those of the other conditions in the amount of localization error (Fig. 3d).

In summary, our results showed a similar trend in mislocalizations to the transient vibration and to the onset of a continuous vibration; mislocalization in the same direction in the early time range was the dominant component. The results also showed a clear difference in the trend in mislocalizations to the onset and offset of continuous vibrations; mislocalization to the offset was observed both in the same direction in the early time range and in the opposite direction in the later time range. It appears that the mislocalizations to the offset exhibit a bifurcation, with some of them in the same direction and others in the opposite direction of the hand movement.

Discussion

Since our experiments were performed without visual guidance, the only available information was the internal representation of the hand movement and the timing information of the sensory input (the vibration stimulus on the nail). The internal representation used for the localization task would be the efferent copy (the copy of a motor command from the central nervous system to move the hand) (Sperry 1950; von Holst 1954), because the participants performed

fast hand movements and afferent information from the periphery would be subjected to significant delays due to the transduction latency of the peripheral nerves. As suggested in the study by Dassonville (1995), the mislocalizations could be due to both an inaccurate representation of the hand movement and the lack of a mechanism to register the timing information. In agreement with this argument and analogous investigations in the peri-saccadic mislocalization literature (Boucher et al. 2001; Georg et al. 2008), our experimental results showed that the mislocalizations differed with different target types.

How can the difference in the onset and offset localizations be explained? Regardless of whether the internal representation is inaccurate or not, it seems that the same internal representation would be referred for the three localization tasks. If so, the dissociation of the time courses between the onset and offset localizations should be ascribed to the difference in the timing information of the sensory input. It is, however, unclear at which level the difference could be generated; it could be in the level of neural signal, encoding, or higher cognitive strategy.

Considering the difference in the level of neural signal, since the time required for the mechanoreceptors to respond to the onset or offset of the vibration makes little difference (Johansson and Westling 1987), the difference in the timing of neural signal, such as that induced by transduction latency, might therefore be a key factor. As shown in Figs. 1c and 1d, it could be assumed that the relatively longer or shorter latencies of the sensory input compared with the latency of the efferent copy result in a mislocalization in the direction of the hand movement before the movement begins, or a mislocalization in the opposite direction during and after the movement, respectively. However, the latencies measured in the simple reaction time task (Fig. 1e and its legend) did not show a consistent tendency in conjunction with the localization results between individuals, though some significant effects ($p < 0.05$) were observed within each individual data set. Primarily, the assumption that the latency is constant throughout a hand movement cannot explain the bifurcation of the offset localization. Although it has been reported that the detection threshold (Dyhre-Poulsen 1975) and the subjective intensity of suprathreshold stimuli (Milne et al. 1988; Post et al. 1994) could be changed at around the time of hand movement, the reason that the different tendency was observed only for offset localization is still unclear.

This discrepancy between localization and latencies might be due to the level of information encoding. An interesting report in the field of visual psychophysics could be related to this discrepancy. Boucher et al. (2001) reported that the mislocalization around the time of saccadic eye movement could be changed by modulations in luminance intensity, which caused fluctuations in processing time in

the brain, and that the amount of change in observed mislocalization did not coincide with the amount expected from the differences in processing time. As observed in the visual modality (Jaskowski 1996; Nishida and Johnston 2002; Terao et al. 2008), in the tactile modality as well, how the timing information is encoded for perceptual tasks such as localization may not directly reflect the timing of the neural signals.

Finally, the difference might be a result from a difference in the localization strategies, which are used at the cognitive level, rather than from the difference in the sensory information processing. A different strategy may be used when the target is an offset, namely, the offset may be mislocalized as having occurred at the center of the hand movement. Another possibility is that, although a typical strategy may be used regardless of target types, other strategies may be used in some trials only when the target is an offset.

In the current paper, we investigated the generality of the mislocalization tendency by observing the haptic localizations in response to different target types, i.e., the onset and offset of continuous vibro-tactile stimuli. The novel finding in this study is that the mislocalization can differ with different target types. Our results suggest that the difference cannot simply be ascribed to distortion in the timing of neural signals, such as that induced by latency differences, indicating instead that it could be explained by taking into account the possibility of differences in the encoding of timing information or in the cognitive strategies for localization.

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