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The range of discrepant directions indicated by visual and vestibular inputs that can be multimodally integrated in the perception of self-motion.

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We investigated the range of directions indicated by vision and vestibular inputs that are integrated when perceiving the direction of self-motion. Self-motion directions are perceived via multimodal integration of visual and vestibular information even in a case, like “vection”, in which these inputs are inconsistent with one another. Although recent studies have shown that these inputs can be integrated with the resulting perceived direction of self-motion in a weighted combination, it remains unclear how wide the integration range is. To examine this range, we conducted an experiment providing inconsistent visual and vestibular information to participants using a rotatable chair on a motor-driven swing and a head-mounted display. Results showed that the weighted combination occurred when the inconsistency between visual and vestibular motion directions was between 60 and 165 degrees.

Key words: perception of self-motion, multimodal integration, visual-vestibular information

Introduction

One way we perceive our environment is by integrating information from multiple senses in Bayesian fashion of weighted combination (Ernst & Banks, 2002). Another, more complex fashion (van Atteveldt, Murray, Thut, & Schroeder, 2014), some sense compensates for or facilitates the processing of other senses. Perception of self-motion is a typical case of such multisensory processing because it is derived from simultaneous visual, vestibular, somatosensory, proprioceptive, and auditory inputs (Palmisano, Allison, Schira, & Barry, 2015). Contributions of visual and vestibular inputs, however, are considered to be greater than other inputs and the integration of these sensory signals has been investigated (Fetsch, DeAngelis, & Angelaki, 2009; Greenlee et al., 2016). Vection is a well-known illusory self-motion perception and is usually categorized as a visual experience induced solely by visual motion input (e.g., optic flow) (Dichgans & Brandt, 1978). However, this illusion is also an extreme case of visual-vestibular integration since the perceptual system has to solve the discrepancy between the visual information indicating that the body is moving and the vestibular information indicating that the body is still.

Intriguingly, recent studies have revealed that vection could be facilitated not only by other visual components like jitter (Palmisano, Gillam, & Blackburn, 2000) but also by other modality inputs like vestibular signals (Wright, 2009; Wright, DiZio, & Lackner, 2005) even

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when vestibular signals have incongruent phase or direction to visual inputs. These results suggest a broad mechanism that integrates visual and vestibular inputs for self-motion perception.

Moreover, perceived directions of linear self-motion can be multimodally integrated from orthogonally directed visual and vestibular stimulation (Sakurai, Kikuchi, Kikuchi, & Misawa, 2003; Sakurai, Kubodera, Grove, Sakamoto, & Suzuki, 2010). When observers passively experience real oscillatory forward/backward somatic motion while viewing leftward/rightward visual flow patterns consistent with rightward/leftward body motion (vection), their perceived self-motion direction is intermediate to those specified by visual and vestibular information individually. Therefore, visual and vestibular information could be integrated according to a weighted combination resulting in the perception of intermediate direction of self-motion even when the vestibular information is inconsistent with visual information to a large degree.

The present study focuses on the range of discrepant directions indicated by visual and vestibular inputs for which visual-vestibular integration occurs. Although many previous studies have examined visual-vestibular integration by means of manipulating the type of visual stimuli, few studies have examined perceived self-motion induced by real physical motion with strict controlled experimental settings. This could be due to methodological difficulties, resulting in little support for visual-vestibular integration with little contribution from vestibular stimuli. Perceived direction of self-motion can be influenced by real physical motion and by the orientation of the head and body with respect to the direction of motion, so it is crucial to elucidate how vestibular information interacts with visual inputs (St George & Fitzpatrick, 2011). In the case of perceived self-motion from visual and vestibular stimuli physically in different directions of motion, the range over which multisensory integration occurs remains unclear. To examine this point gives us the weighted combination range of visual-vestibular integration; what is the limit of this integration.

Here we investigated the limit of visual/vestibular integration by introducing angular inconsistency of body-motion direction from visual motion direction and measuring perceived direction using a rod-pointing task and its confidence rate.

Method

Participants:

Eleven students of Tohoku Gakuin University (6 females, mean age = 20.36 years, *SD* = 0.98) participated in this study. All participants had corrected-to-normal vision and had no hypersensitivity to motion sickness.

Apparatus:

A rotatable chair on a motor-driven parallel swing and a head-mounted display (NVIS: nVisor SX) were used for stimulus presentation. The experiments were controlled by the Psykinematix software (KyberVision Japan) running on a MacPro computer (Apple) connected to a Bits # visual stimulator and an AudioFile device (Cambridge Research Systems).

Stimuli:

The visual stimuli consisted of translating vertical sine-wave gratings (0.1 cycles per degree) phase-locked to the swing motions. The oscillation frequency was 0.33 Hz and the amplitude was 1 cycle. The vestibular stimulation was provided from somatic oscillatory motion with one of 13 orientations of the chair (0 to 180 degrees in 15-degree intervals) relative to the path of the swing. The oscillation frequency was 0.33 Hz and the amplitude was 50 mm (100 mm displacement from peak to peak). In the 0 degree condition, the participants' leftward/rightward somatic motion and its phase were consistent with the visual stimuli, while they were inconsistent in all other conditions.

Procedure:

While participants were seated on the oscillating motor-driven swing viewing the oscillating visual stimulus, they were sound-cued to indicate their perceived direction of self-motion via a rod-pointing task, and then indicated their confidence of judgments on a 5-point scale (1: no confidence, 5: absolutely confident). Auditory pink noise was continuously presented during the experiment through the earphones of the head-mounted display. Three measurements for each of 13 orientation conditions were performed. The order of trials was randomized across the participants.

Results

The perceived directions of self-motion were intermediate to those specified by visual and vestibular inputs in the range of 60-180 degree conditions (Figure 1). In 0, 15 and 30 degree conditions, the perceived self-motion directions were not intermediate, rather, participants overestimated their directions of real body motion. In 45 degree condition, the perceived self-motion direction was almost the same as the visually induced self-motion direction, suggesting that the process of multimodal integration was in transition from non-weighted to weighted at this point. In 60-180 degree conditions, the weighted combination occurred especially in 60 and 180 degree conditions where the perceived direction was nearly the mean value of the visual and vestibular directions while the vestibular information was weighted more heavily in the 75-165 degree conditions.

All confidence ratings were close to the mean value (*Mean*=2.61), and one-way ANOVA with repeated measures showed no significant difference among them ($F(5.036, 50.360) = 1.628$, $p = 0.169$) (Figure 2). Since Mauchly's Test of Sphericity was statistically significant ($p < .05$), Greenhouse-Geisser correction was applied.

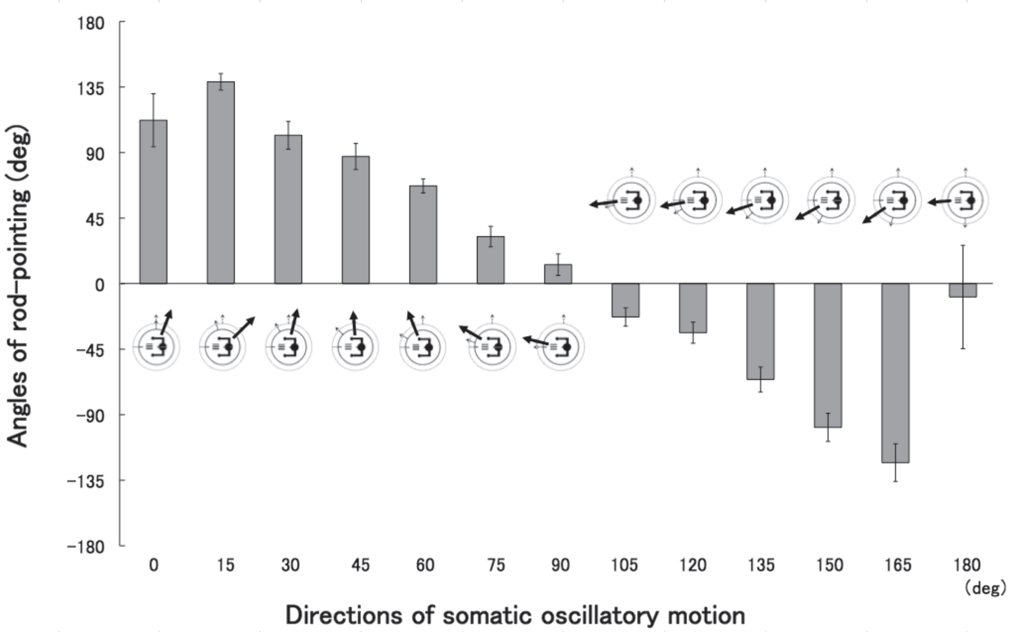

Figure 1. Perceived self-motion directions from real body motion and visually induced self-motion. Each arrow of the circle images in the figure represents the direction of perceived self-motion (large black), the direction of real body motion (dashed grey), and the direction of visually induced self-motion (upward-solid gray).

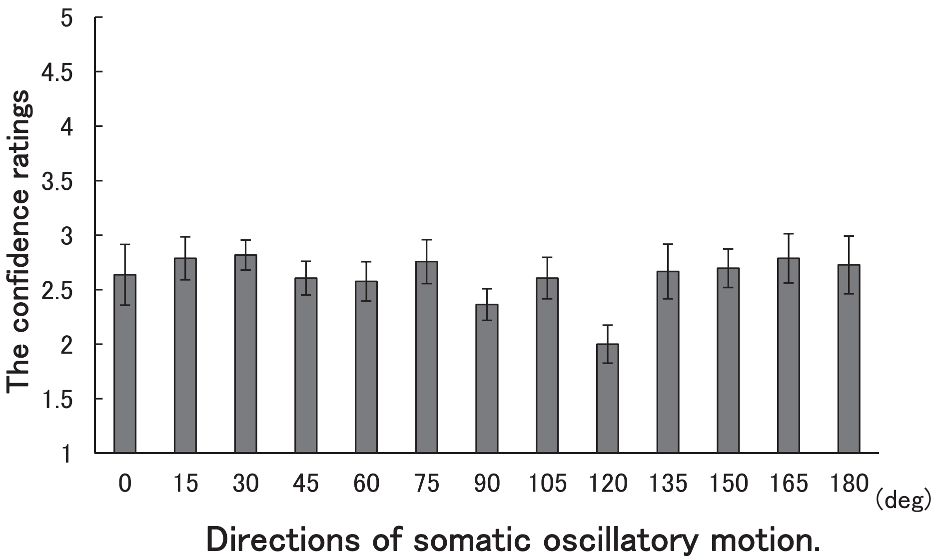

Figure 2. Mean values of confidence ratings for each orientation condition.

Discussion

The perceived direction of self-motion from visual and vestibular information was multimodally integrated for inputs specifying directions that differed from 60 to 165 degrees, suggesting that the weighted combination stably occurs when there is certain angular inconsistency between visual and vestibular information.

It is assumed that the weighted combination of multimodal integration induced by visual and vestibular information is most robust when the angular inconsistency between these motion directions is approximately 60 degrees. Although the result of rod-pointing in 180 degree condition showed that perceived direction was clearly an intermediate estimate of the two inputs similar to the 60 degree condition, participants' responses were outputs of an either-or process rather than those of weighted combination process. The large error bars associated with those estimate suggest a bimodal distribution of responses. The vestibular information was more weighted in 75-165 conditions and became dominant in multimodal integration with large angular inconsistencies. One possible account for this result is that instances in which visual information is very inconsistent with vestibular information are likely to be rare in natural viewing conditions because of the horizontal eye rotation limit. Considering the fact that we are able to look sideways up to +/- 45 - 50 degrees with the head fixed (Howard, 1982), visual information inconsistent with vestibular information in this range should be easily integrated. The inconsistent visual inputs with vestibular ones beyond +/- 45 degrees, however, might be less reliable in the weighted combination process. The results of overestimated perceived self-motion directions in 0 and 15 degrees support the previous studies that observers tend to overestimate their perceived directions of self-motion when there is little inconsistency between the visual and vestibular motion directions (Cuturi & MacNeilage, 2013).

From the results of confidence ratings, there was no difference while the perceived self-motion directions changed. This suggests the difficulty in judging the perceived self-motion direction was equal across all conditions.

In this study, we focused on the range of directions indicated by vision and vestibular inputs that are integrated when perceiving the direction of self-motion using a parallel swing. Further studies are needed which examine the range of the integration on sagittal and coronal planes in order to elucidate the limits of stable integration between visual and vestibular information.

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