Spatial modulation of multisensory integration of visual and tactile motion —Evidence from the redundancy gain paradigm—

Hiroshi USHIODA and Yuichi WADA
Tohoku University*

In two experiments, the redundancy gain paradigm (Miller, 1982) was employed to examine whether redundant visual and tactile motion signals are integrated across these two modalities, and how the spatial relationship of visual and tactile signals affects cross-modal integration. A visual motion stimulus and/or a tactile motion stimulus were presented, and participants had to identify the motion direction of stimuli from each modality as quickly as possible. It is well known that faster reaction times are observed for bimodal stimuli than for unimodal stimuli; this facilitation is termed redundancy gain (RG). The present study manipulated the spatial relationship between the visual and tactile motion stimuli to assess reaction time distributions and the magnitude of the RG. Results indicate that visual and tactile motion signals are most effectively integrated when visual and tactile stimuli are presented in the same spatial location.

Key words: cross-modal integration, visuo-tactile, motion perception, redundancy gain

In our environment, a dynamic event provides various types of sensory information, such as visual, auditory, and tactile information. The perceptual system in the human brain integrates these signals to create a single representation of the event. There has been a great deal of interest in pursuing the way in which sensory signals from different modalities integrate.

From an evolutionary point of view, motion perception is one of the most important perceptual functions for survival. Our survival in a complex environment has likely depended upon (among other things) an ability to extract from dynamic signals the motions of objects as well as living things which may be potential predators or prey animals. For many animals, including humans, vision is likely to be the primary source of sensory information of motion signals. Although visual motion signals typically tend to dominate over motion signals in the other modalities (Soto-Faraco, Kingstone, & Spence, 2003), we can also extract motion information from hearing a sound or feeling a tactile stimulus. For example, consider the way we perceive an approaching vehicle; typically, we respond to the changing retinal size (looming) of such an object, but we are also sensitive to the correlated rate of increasing sound intensity created by an oncoming car. By the same token, we can feel tactile sensations of an insect crawling down one’s arm in accordance with its visual localization.

Although a majority of research on multisensory interaction processes has addressed the integration of static events, only recently have some authors have sought to examine multi-sensory integration of motion signals (Alais & Burr, 2003; Meyer & Wuerger, 2001; Meyer, Wuerger, Rohrbein, & Zetzsche, 2005; Wuerger, Hofbauer & Meyer, 2003). These studies focused upon benefits that might arise from multiple presentations of motion signals: that is, they find that detection performance involving a single event is facilitated when the event conveys multiple motions signal from respectively different modalities rather than information from only a single modality.

While significant evidence for the integration of visual and auditory motion signals has been reported, considerably less is known about the integration of visual and tactile motion signals. However, some evidence appears to reflect a visual-tactile interaction in motion perception involving motion direction. For instance, Craig (2006) found that accuracy in judging the direction of tactile apparent motion declined when presented simultaneously with visual apparent motion that drifted in a direction opposed to that of the tactile motion (versus when presented in the same direction). Using a similar paradigm, Bensmaia, Killebrew, and Craig (2006) found that a task-irrel-

* Graduate School of Information Sciences, Tohoku University, 6-3-09 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8579, Japan

Copyright 2012. The Japanese Psychonomic Society. All rights reserved.
event visual grating drifting in the same direction as a tactile motion increased perceived speed of the latter. Although these studies demonstrated that the relative direction of visual motion signals can modulate percepts of tactile motion signals, they merely illustrate a cross-modal interaction; however, they do not provide direct evidence for multi-sensory integration per se. Thus, the existence of cross-modal integration for motion signals between vision and touch remains to be conclusively established.

In the present study we attempted to provide evidence for cross-modal integration of motion signals between vision and touch. To address this issue, we employed a frequently used paradigm, known as the redundancy gain paradigm (Miller, 1982). This paradigm permits assessment of integration of multisensory signals from different modalities. It requires participants to respond to two target signals from respectively different modalities which are presented either alone or simultaneously. These two modality motions (i.e., bimodal targets) are considered redundant motion signals when the same response is required for the targets from each of the different modalities. It has been shown that the reaction times (RTs) to bimodal targets are faster than those to unimodal target signals; this is the redundant-signals effect. It reflects a facilitation termed the redundancy gain (RG) effect (i.e., redundant-signals effects). It has been assumed that this redundancy facilitation is due either to a probabilistic summation of unimodal signals from different sensory modalities (a race model) or from a sensorimotor facilitation resulting from the convergence of the incoming signals, suggested by a co-activation model.

Because a race-model predicts that signals from two modalities independently compete to evoke a response initiation and the response is elicited by the winner of a race between two processing processes in bimodal trials. Since the likelihood of either of two signals yielding a fast reaction time is higher than that from one signal alone, the average RT for the winner of the race in bimodal trials will be shorter than the average RT of either of unimodal trials (Raab, 1962). Thus, simple probability summation could produce the RG effect. According to a co-activation model, the processing pathways of both modalities converge somehow at a particular stage whose processing efficiency is increased by multimodal input. This could result in faster responses to bimodal stimuli, yielding the RG effect. As Miller (1982) has pointed out, a race model makes the strong prediction that the RT on bimodal trials cannot be shorter than the shortest RT on unimodal trials. A co-activation model is accepted when the RG is larger than predicted by the race model assumption. Miller (1982) developed a method termed the race-model inequality test, to assess different predictions from these two models. According to this test, a violation of the predicted distribution inequality by the race model is considered as a support of the co-activation model, implying multi-sensory integration of sensory inputs. A number of studies have shown that that a violation of the race-model inequality test results from cross-modal interactions, mostly with visual and auditory interactions (Diederich & Colonius, 2004; Miller, 1982, 1986; Schwarz & Ischebeck, 1994), but also with visual and tactile or somatosensory ones (Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002; Murray, Foxe, Higgins, Javitt, & Schroeder, 2001).

Experiment 1 was aimed at establishing the RG effect with visual and tactile motion signals. First, RTs to redundant motion targets were compared with those to unimodal targets, because the RG effect provides a simple index of multi-sensory advantage. Second, Miller’s race-model inequality tests (1982) were used to ascertain whether RG effect, if present, violates the race model inequality. If it does, then this is strong evidence for strong evidence for visual-tactile integration of motion signals.

**Experiment 1**

**Method**

Participants. Eleven undergraduate and graduate students (including the authors HU and YW) at Tohoku University participated in the experiment. All had normal or corrected-to-normal vision.

**Apparatus and Stimuli.** A schematic view of the experimental apparatus is shown in Figure 1. Stimulus presentation and data collection were controlled by an IBM-compatible computer running custom-written software (written in C) that incorporated routines for synchronizing vibrotactile and visual stimuli.

The tactile stimuli were presented on the left forefinger pad of a participant through a vibro-tactile stimulator (Optacon II: Model R2B, Telesensory Systems Inc.); the stimulator was located on a table in front of the participants. The tactile stimulus was a simulated dynamic line pattern consisting of a horizontal array of five activated tactors. This pattern began to shift from the center of a forefinger pad in either the backward or forward direction at a velocity of 3.0 cm/s (corresponded to visual angle 3.0 deg/s). The intensity of the vibrotactile stimu-
The distance on tems), rate), ment (visual motion stimuli, white light was stabilized by a chinrest to ensure that the visual and tactile stimuli were presented along the same horizontal plane. The visual stimulus was presented either within two rectangular boxes (2.2°×4.0° of visual angle) that were centered 8.0° to the left and right of a white fixation cross (56 cd/m²) on a grey background (18 cd/m²). It was a dynamic pattern consisting of a white line pattern (56 cd/m²) that moved with constant velocity from the center of a fixed rectangular box, in either a backward or forward direction within this box. The spatial alignment of the dynamic visual line pattern corresponded to the locations of the tactile line pattern throughout both motion patterns. Both visual and tactile motion signals moved simultaneously with same velocity (3.0°/s), over corresponding shifts in space.

Procedure. Prior to the experiment, participants performed practice blocks for approximately 10 minutes until they became familiar with the stimuli and the task. Each trial began with the presentation the presentation of a fixation cross and two rectangular boxes, and 1000 ms later a bimodal (visual and tactile) or unimodal (visual or tactile) targets was presented. The drifting direction of visual and/or tactile targets was determined randomly for each trial. Participants were instructed to judge as quickly as possible if the target was moving either in the forward or backward direction using one of two corresponding keys with right hand. To nullify any auditory cues generated by the vibro-tactile stimulators, white noise was presented throughout the entire experiment over headphones (Sony MDR-CD570) at 70 dB SPL to mask any sounds made by the operation of the vibro-tactile stimulator.

Design and conditions. Three different modality conditions were bimodal, visual, and tactile. In the bimodal condition, visual and tactile stimuli were presented simultaneously at the same location, and always had same directions. In the visual or tactile conditions, only visual or only tactile stimuli were respectively presented. A two factor design crossed the three modality conditions (bimodal, visual, tactile) with two motion direction conditions (forward, backward). Each participant completed 360 trials in total, divided into three blocks of 120 trials, with 60 trials in each modality condition for each direc-

Figure 1. (a) A diagrammatic illustration of the experimental apparatus and stimuli. The visual stimulus was generated on a CRT monitor placed above the participant’s head, and was projected onto a semi-silvered mirror. Participants’ hands were positioned beneath the mirror. The tactile stimulus was generated by a vibro-tactile stimulator (Optacon). In Experiment 1, the tactile stimuli were presented on the participants’ left forefinger pad. In Experiment 2, they were presented on both left and right forefinger pad by two vibro-tactile stimulators placed bilaterally on the table. (b) A schematic view of visual and tactile stimuli. Visual stimulus was a single line pattern which drifted within a rectangular box. Tactile stimulus was a simulated motion line pattern consisted of a linear array of five activated tactors. Visual and tactile motion stimuli moved in either the backward or forward direction.
Results and Discussion

Trials in which a participant's RT exceeded ±2 standard deviations from the mean RT and trials for which a participants made incorrect motion direction responses were excluded from the data.

Results of mean RT data are shown in Table 1. In first analysis, the mean RTs for all conditions were compared to confirm the RG effects from redundant visual and tactile motion signals. The RT data was analyzed by means of a two-way repeated measures analysis of variance (ANOVA), with two withinsubjects factors of modality (bimodal vs. visual vs. tactile) and motion direction (backward vs. forward). An ANOVA showed significant main effects of modality condition ($F(2, 20)=46.12, p<.0001$) and motion direction ($F(1, 10)=15.98, p<.005$), and a significant interaction between modality condition and motion direction ($F(2, 20)=7.37, p<.005$).

Simple main effects analysis confirmed that the effects of modality condition were significant for both of the motion direction (backward: $F(2, 40)=44.51, p<.0001$; forward: $F(2, 40)=30.81, p<.0001$). Multiple comparisons (Holm-Bonferroni method with alpha set at 0.05) showed that the RTs to the bimodal targets were significantly faster than those to either visual or tactile target for each motion direction. In order to obtain very conservative RG effects, further analysis compared the RT of bimodal condition with the faster RT between visual and tactile condition for each participant (unimodal condition) each motion direction. As a result, the RTs of bimodal conditions were still faster than those of unimodal conditions regardless of motion direction $[n(9)>6.74, p<.001]$. The significance of the difference was not affected by a log transformation of the RTs. These results showed that the RG effects were found with visual and tactile motion stimuli, consistent with previous studies using static targets (Diederich & Colonnus, 2004; Forster et al., 2002; Miller, 1982).

Next we determined if the observed RG effects violated race model inequality. We tested race model assumptions of independence of the cumulative distribution functions (CDFs) of RTs for different modality conditions. Accordingly CDFs were calculated for visual, tactile and bimodal conditions for each motion direction for each participant. To compare bimodal and unimodal conditions according to the race model inequality, this analysis computed the sum of visual and tactile CDFs (sum unimodal CDFs), and compared this summed unimodal distribution with the bimodal CDF in each motion direction (Figure 2). The CDFs of bimodal and unimodal conditions were analyzed by means of an one-tailed $t$-test ($p<0.05$ for matched pairs) at each of the 10 percentile points (5th, 15th, 25th and so on). In the backward condition, the CDF for bimodal condition was significantly faster than those for unimodal condition from 15th percentile to 45th percentile. Similarly, the forward condition also revealed significantly faster RTs for bimodal condition than for unimodal condition from 5th percentile to 45th percentile.

These results demonstrate that RG effects emerged in visual and tactile motion signals, and that the RG effects are consistent with a co-activation model rather than with a race model. The present findings suggest that visual and tactile motion signals were integrated across modalities; thus, they are consistent with previous studies that have shown multi-sensory enhancement of motion signals between vision and audition.

---

1 One reviewer was concerned that the random target sequences provide possible modality switches only at the unimodal trials. It has been shown that the RTs are slower when the target is preceded by the target for a different modality (Spence, Nicholls, & Driver, 2001). Thus, the bimodal facilitation is possible to be due not to the bimodal processing gain, but to the modality switch costs at the unimodal trials (Gondan, Lange, Rosler, & Roder, 2004). However, the RG effects were still significant when we added additional unimodal-only blocks in which only visual or tactile stimuli were presented through each block, and adopt this data as the unimodal RTs for analysis (Ushioda & Wada, 2007). We confirmed that the results obtained with this "blocked trials" procedure were essentially the same as that observed in the current study, demonstrating that the RG effects cannot be attributed to the modality switch costs at the unimodal trials.
The Japanese Psychonomic Society

H. Ushioda and Y. Wada: Spatial modulation of multisensory integration of visual and tactile motion

Figure 2. Cumulative distribution function (CDF) of RT for each motion direction in Experiment 1. Open circles refer to the CDF for bimodal condition, and filled squares refer to the sum of two CDFs for visual and tactile conditions.

Figure 3. The magnitude of redundancy gain (RG) for each participant as a function of RT difference between visual and tactile conditions in Experiment 1. Downward and upward triangles refer to the backward and forward motion direction, respectively.

(Soto-Faraco et al., 2003).

The primary purpose of this analysis was to confirm that RG effects obtain with visual and tactile motion signals. However, the analysis of mean RTs also showed a significant main effect of motion direction and a significant interaction between modality and motion direction. Post hoc analysis revealed that the RTs to forward direction were significantly faster than those to backward direction in bimodal condition (F(1, 30) = 10.01, p < .005) and tactile condition (F(1, 30) = 25.20, p < .0001), whereas no directional difference appeared in the visual condition (F(1, 30) = 0.17, p = .68). The difference observed in tactile condition could be accounted for by the following explanation. The tactile motion stimulus used in this study was a single line pattern which emerged at the center of a forefinger pad, and then began to move in either a backward or forward direction. This means that the backward and forward tactile motion pattern first stimulated either the bottom or top side of a forefinger pad, respectively. Previous neurophysiological studies have shown that tactile sensors sensitive to transient stimulation are mainly distributed on the top of a forefinger pad rather than on the bottom (e.g., Talbot, Darian-Smith, Kornhuber, & Mountcastle, 1968; Vallbo & Johansson, 1978). Thus, this type of sensors on the top of a forefinger pad presumably produced the faster detection speeds for the forward motion stimuli.

This raises a question concerning a difference found in the bimodal condition. In this condition the size of the RG effect differed with direction; RG for the forward direction (25 ms) was greater than that for the backward direction (17 ms). However, the RTs for the unimodal conditions the RTs (faster RTs from each of the two single modality conditions) did not differ due to direction. A possible explanation is that the RT difference between visual and tactile conditions is related to the magnitude of RG effect. Here we calculated the RG values for each motion direction for each participant, then produced a correlation coefficient between the RT difference of unimodal conditions and the obtained RG (Figure 3). As a result, a significant negative correlation was found (r = −0.48, p < .05), indicating that smaller differences in the RT difference of unimodal conditions accompany correspondingly greater RGs. If we regard the small RT differences between visual and tactile conditions as support for the notion that the time course of sensory processing is similar for both stimuli, these results seemed to be in line with the previous studies with static stimuli showing that the largest RG was observed when two unimodal RTs were temporally co-occurred (Diederich & Coloni-
from each other for revealing the effect in the condition (the "far" condition) in which the two stimuli were presented in different spatial positions. This leaves some uncertainty as to the reality of null effect of the spatial separation for visual-tactile motion perception.

Therefore we thought it worthwhile to determine whether the cross-modal motion integration was modulated by the spatial relationship between the tactile and visual stimuli. Accordingly, in Experiment 2 we investigated RG effects as a function of variations in spatial locations of visual and tactile stimuli in order to assess integration effects using the race-model inequality test. If it is the case that the spatial coincidence plays a role, then we should find larger RG effects along with violations of the inequality test for multisensory integration when the tactile and visual stimuli appear at the same spatial locations than when they appear at spatially distinct locations. Thus in Experiment 2, the visual and tactile motion stimuli were presented either at same location or at different locations.

Method

Participants. Thirteen undergraduate and graduate students at Tohoku University participated in this experiment. Except for the authors HU and YW, all participants were naive to the experimental manipulations.

Apparatus and Stimuli. This experiment used two vibro-tactile stimulators which were placed 13.0 cm apart (horizontally) on the table in front of the participants. One of the two vibro-tactile stimulators was for participants' left forefinger pad, and the other for the right forefinger pad. In each trial, a tactile stimulus was presented at either left or right forefinger pad. Similarly, visual stimuli were presented at either left or right side of a central fixation cross with two fixation boxes positioned 6.5 degrees left and right of the fixation cross (correspond to the locations of tactile stimuli).

Procedure. Each trial began with the presentation of a fixation cross and two fixation boxes and 1000 ms later targets were presented. Participants judged motion direction using one of two corresponding foot pedal with right foot.

Design and conditions. In this experiment, the condition for bimodal condition was divided into two different bi-modal conditions by the spatial separation: matched bimodal (m-bimodal) and unmatched bimodal (u-bimodal). In the m-bimodal condition, visual and tactile stimuli were presented at same location in either left or right side, whereas in the u-bi-
modal condition, the stimuli were presented at different locations separately. In the visual or tactile condition, only visual or only tactile motion stimuli were presented at either left or right side.

To equalize the occurrence rate of bimodal stimuli with that in Experiment 1 (a third of total trials was for bimodal condition), the numbers of m-bimodal and u-bimodal trials were half of the visual and tactile trials (50 trials for m-bimodal and u-bimodal and 100 trials for visual and tactile × 2 motion direction conditions × 2 locations). Thus, each participant completed 1200 trials in total, divided into ten blocks of 120 trials.

Results and Discussion
Table 2 shows the mean RTs for all conditions. The data were analyzed by means of a two-way repeated measures ANOVA with factors of modality conditions (m-bimodal vs. u-bimodal vs. unimodal) and motion direction (backward vs. forward). There was a significant main effect of modality condition ($F(2, 24) = 72.52, p < .0001$) and a significant interaction between modality condition and motion direction ($F(2, 24) = 4.32, p < .05$), whereas there was no significant main effect of motion direction ($F(1, 12) = 0.14, p = 0.71$). Simple main effects analysis confirmed that the effects of modality condition were significant for both motion directions (backward: $F(2, 48) = 24.10, p < .0001$; forward: $F(2, 40) = 40.87, p < .0001$).

Table 2
Mean RTs (ms) (SD in parentheses) for each experiment condition in Experiment 2. The mean RTs for unimodal condition is faster RT between visual and tactile condition for each participant.

<table>
<thead>
<tr>
<th>Motion direction</th>
<th>Bimodal (matched)</th>
<th>Bimodal (unmatched)</th>
<th>Visual</th>
<th>Tactile</th>
<th>Unimodal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backward</td>
<td>352 (29.0)</td>
<td>358 (30.4)</td>
<td>370 (29.8)</td>
<td>411 (36.8)</td>
<td>370 (29.8)</td>
</tr>
<tr>
<td>Forward</td>
<td>346 (24.6)</td>
<td>355 (24.8)</td>
<td>375 (22.3)</td>
<td>393 (32.2)</td>
<td>373 (23.7)</td>
</tr>
</tbody>
</table>

Figure 4. CDFs of spatially matched and unmatched conditions for each motion direction in Experiment 2. Open circles refer to the CDF for bimodal matched or unmatched condition, and filled squares refer to the sum of two CDFs for visual and tactile conditions.
Multiple comparisons showed that the RTs for the m-bimodal and u-bimodal conditions were faster than those for unimodal condition for both motion directions; more importantly, the RT of the u-bimodal condition was significantly slower than those of the m-bimodal condition.

Next, CDFs for the m-bimodal and u-bimodal conditions were compared with the sum of the visual and tactile conditions (Figure 4) in order to test whether the observed RG effects violate the race model inequality. As in Experiment 1, the CDFs of bimodal and unimodal conditions were analyzed by means of an one-tailed t-test ($p < 0.05$ for matched pairs) at each of the 10 percentile points (5th, 15th, 25th and so on). Results showed that violations of the race model occurred in the m-bimodal condition; significant differences between bimodal and unimodal conditions occurred for percentiles between 0 and 25 for the backward motion condition and between 0 and the 45th percentile in the forward motion condition. However, in the u-bimodal condition, a far smaller violation was found, and this emerged only at 15th percentile point in the forward condition.

Experiment 2 replicated the basic results of Experiment 1 for the modality condition in which visual and tactile motion stimuli occurred at the same spatial location. On the other hand, when visual and tactile motion stimuli were positioned separately, the RG effects decreased appreciably and the violation of race model inequality almost vanished, thus implying that the spatial separation is a critical factor for integrating visual and tactile motion signals. This finding is in line with a similar study which combined visual motion signals with auditory ones (Meyer et al., 2005); in the latter research, the spatially unmatched visual and auditory motion signals produced a small reduction in the detection threshold in the extent of probability summation. Spence, Pavani, and Driver (2004) also showed that the effects of a visual distractor on detection performance in a tactile localization task were considerably diminished when a visual distractor was presented at a location of the tactile stimulation but on the opposite hand. On the other hand, as mentioned earlier, Craig (2006) has reported contradictory results, in which visual motion information robustly influenced tactile motion perception even when their locations were spatially unmatched.

Several noteworthy methodological differences distinguish the present study from Craig’s and they render difficult direct comparisons across the two studies. For instance, in Craig’s experiment the main dependent variable involved cross-modal interference effects caused by task-irrelevant visual motion. In addition, the spatial separation (13 cm) in the unmatched conditions (u-bimodal) of the present study differs from those in the Far condition of Craig’s study. In the current study visual and tactile motion stimuli were presented in the opposite hemispheres whereas in the unmatched condition in Craig’s study, tactile stimuli and visual stimuli appeared in the same hemisphere. That is tactile stimuli were presented only at the left forefinger pad, and spatially unmatched visual stimuli were located along the vertical meridian. Thus, although positions of the visual and tactile stimuli in Craig’s design were spaced 29.5 cm apart, they were vertically aligned, meaning that the two stimuli appeared in the same hemisphere. In this regard, we can assume that the stimulus setting in Craig’s study might generate multisensory motion sensation that originates from the same event. The vertical alignment of two stimuli may have provided sufficient cues to encourage perceptual grouping, and consequently, the two motion signals may have been treated as a single motion stream. As highlighted above, co-occurrence of temporal and spatial stimuli is considered to an important factor for multisensory integration (Stein & Meredith, 1993). In this regard we can assume that parsing inputs into one perceptual group could facilitate multisensory integration. This could be a possible explanation for Craig’s (2006) failure to observe any effects of spatial separation in his study. Clearly, at this point, this explanation is speculative. It also should be noted that in Forster et al. (2002) the RTs for bimodal stimuli presented at different hemispheres did not significantly differ from those presented at same hemisphere (see also Strybel & Vatakis, 2004). As the present study has not systematically manipulated the spatial distance or alignment between the visual and the tactile stimulus location, we cannot directly address the question of how the spatial distance or alignment of bimodal stimuli affect the degree of RG effects quantitatively. Thus, future research should further investigate the role of spatial factors on multisensory motion integration between vision and touch.

**General Discussion**

The present study used the redundancy gain paradigm to ascertain whether redundant visual and tactile motion signals produce greater performance on motion direction discrimination than single visual or tactile signal, and whether performance depends upon the spatial separation of visual and tactile stimuli.
In Experiment 1, it was shown that the detection speed for the motion direction of visual and tactile targets was significantly faster than the response speed for visual or tactile unimodal targets, i.e., an RG effect. An important finding in this experiment was that the RG effect was well explained by a co-activation model rather than a race model. This implies that the observed RT facilitation in certain bimodal conditions may be explained by a neural summation process rather than by a probability advantage. Although some empirical data have shown possible cross-modal links in the processing of visual and tactile motion information (Bensmaia et al., 2006; Craig, 2006), to our knowledge, the present study is the first to show a significant RG effect and to demonstrate the violation of race model inequality with visual and tactile motion signals. As such Experiment 1 is consistent with the hypothesis that visual and tactile motion signals are integrated across sensory modalities.

In Experiment 2, spatial separation of visual and tactile stimuli significantly reduced the RG effects relative to those observed for spatially coinciding stimuli. Furthermore, whereas the spatially coinciding stimuli the RG effects were consistent with a co-activation model, the RG effects found for spatially separated conditions were more in line with a race model. That is, when visual and tactile signals are positioned separately they appear to be processed by the independent detection systems. It should be noted a significant violation of the race model inequality was observed in the unmatched condition in Experiment 2, suggesting limitations on inferences of totally independent systems. In this case, however, the violation was quite modest and restricted to a very narrow range of percentile points of the RT data. Nevertheless, it suggests that we cannot firmly conclude that visual and tactile motion signals are not integrated even when sources of these signals are spatially separated. Based on the results of this study, it is not clear why the latter phenomenon occurred. From the fact that we can see an obvious difference in the results of the race model inequality test between the matched and unmatched conditions, we believe that the results of our second experiment reflect the spatial modulation on efficiency of multisensory integration between vision and touch.

The possibility remains, however, that the reduction of detection performance due to spatial separation in Experiment 2 resulted from possible factors associated with spatial attention (Spence & Driver, 1997). When visual and tactile stimuli were presented at different locations, divided spatial attention could produce slower RT for detecting the two signals in different locations than RT for detecting signals occurring at the same location. If this were the case, then one might assume that the spatial modulation of RG effects observed in Experiment 2 is the result of cross-modal consequences of spatial attention. However, this potential argument is weakened in the light of several recent findings suggesting that multisensory integration can occur prior to or independent of attentional selection (Bertelson, Vroomen, De Gelder, & Driver, 2000; Driver, 1996; Soto-Faraco, Ronald, & Spence, 2004; Vroomen, Bertelson, & de Gelder, 2001).

However, as noted by McDonald, Teder-Sälejärvi, and Ward (2001), it is difficult to unambiguously separate the processes of multisensory integration and spatial attention in some experimental paradigms. This is because the two effects can coexist and produce additive facilitation of responses to targets. In addition, because attention is considered to play a critical role in the integration of stimulus features within a single sensory modality (e.g., Treisman & Gelade, 1980) it is not unreasonable to assume considerable overlap obtains between the processes of multisensory integration and that for cross-modal spatial attention. In this regard, Oruc, Sinnett, Bischoff, Soto-Faraco, Lock, and Kingstone (2008) reported that attention did modulate the degree to which the motion signals are combined across modalities at least in some cases. It remains unclear, however, whether integration process occurs preattentively for all kinds of multisensory events without employing attention, or whether attended objects are integrated differently from those that are not attended. It is also unclear whether attention affects the efficiency of integration of stimulus features across different sensory modalities. As there were no direct manipulations of attention in the present study, further work is needed to reveal the possible role of spatial attention on the effectiveness of integrating two or more sensory inputs.

Overall, the present study demonstrated that redundant visual and tactile motion stimuli facilitated detection performance, and that the performance was most efficient when two motion stimuli were co-localized. These behavioral results are supported by the multi-modal neural mechanisms demonstrated in several previous neuro-psychological and neuro-physiological studies (Hagen, Franzen, McGlone, Essick, Dancer, & Pardo, 2002; Stein & Meredith, 1993; Stein, London, Wilkinson, & Price, 1996). The fMRI study for human brain demonstrated that tactile motion stimuli activated middle temporal/V5 complex (MT/V5) area which has been consid-
erated as a unimodal visual area for motion stimuli (Hagen et al., 2002). Moreover, bimodal neurons have been found in the superior colliculus of the cat; these neurons appear to be responsible for multi-sensory interactions between different sensory signals were dependent on the spatial alignment of receptive fields (Stein & Meredith, 1993). It is possible that these neural mechanisms are based on the behavioral facilitation from redundant visual and tactile motion signals, as shown in the present study.

References


—Received Oct. 27, 2010; Accepted Nov. 8, 2011—