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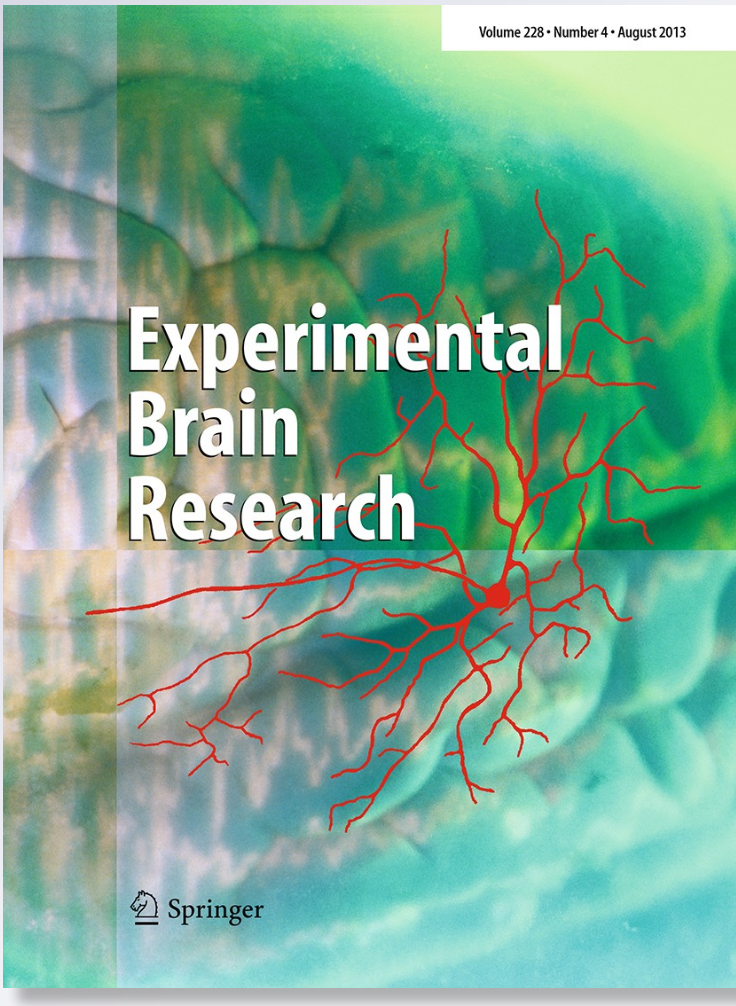

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RESEARCH ARTICLE

Audiotactile interactions beyond the space and body parts around the head

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Abstract Recent research has reported that spatial modulation effects of audiotactile interactions tend to be limited to the space and body parts around the head. The present study investigated the generality of this finding by manipulating body parts stimulated and spatial relationships between the body parts and sounds. In Experiment 1, tactile stimuli were presented randomly to either left or right cheek, hand (palm or back) placed near the head, and knee while auditory stimuli were presented to either the same or opposite side from loudspeakers close to the head. Participants made speeded spatial discrimination responses regarding the side (left versus right) of the tactile stimulation. For any body part stimulated, the performance was worse when the auditory stimuli were presented from the opposite side rather than from the same side. Experiment 2 demonstrated that the spatial modulation effects for the palm or the back of the hand occurred irrespective of hand position (near or far from the head) and sound position (near or far from the head). The sounds delivered from near the head exerted a greater influence on tactile spatial discrimination performance as compared with the sound delivered from far from the head. Furthermore, the back of the hand was more influenced by the auditory stimuli than the palm when the hands were placed near the sounds. These results suggest that the spatial modulation effects of audiotactile interactions can occur beyond the space and body surface around the head.

Keywords Audition · Touch · Audiotactile interaction · Crossmodal distractor interference

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Introduction

Events in the external world often generate concurrent inputs to several different sensory modalities. Therefore, the brain must appropriately select and bind information from different sensory modalities to create an integrated and unified percept of objects and events. How the brain knows which information to integrate is a fundamental question. Most studies on multisensory interactions have identified co-localization in space as a basic rule for binding information from multiple sensory modalities (Meredith and Stein 1986; Stein and Meredith 1993). For example, the ventriloquism effect (Howard and Templeton 1966), in which the spatial location of an auditory stimulus is captured by a spatially disparate visual stimulus, is weakened when the audio-visual spatial separation is very large (e.g., Jackson 1953; Slutsky and Recanzone 2001). For perceptual-level integration in audio-visual motion perception, spatial co-localization is necessary (Meyer et al. 2005). In addition, electrophysiological studies of the superior colliculus and cortex of cat have shown that the receptive fields of neurons that respond to stimulation from multiple sensory modalities are approximately spatially aligned (Meredith and Stein 1986; Stein and Meredith 1993). This spatial-colocalization rule applies not only to audiovisual interactions but also to visuotactile interactions (e.g., Spence et al. 2001).

In audiotactile interaction, however, the spatial modulatory effects have not always been salient. Whether the effects occur is likely to depend on the space in which the auditory stimuli are presented, rather than just spatial colocalization. While most studies in which auditory stimuli were presented in front of or far from participants fail to show clear spatially modulated audiotactile interactions (Lloyd et al. 2003; Murray et al. 2005; Zampini et al. 2005a, 2007), studies in which sounds were presented in the space immediately surrounding the head (peri-head space) have shown these interactions (Kitagawa et al. 2005; Occelli et al. 2010; Tajadura-Jiménez et al. 2009).

Zampini et al. (2005a, b) showed no difference in temporal order judgment (TOJ) performance between audiotactile stimulus pairs presented from different spatial positions and those presented from the same position. In their study, the auditory stimuli were presented directly in front of the participants. In addition, Murray et al. (2005) and Lloyd et al. (2003) reported no or very weak effects of spatial colocalization on audiotactile interactions using simple detection and elevation discrimination tasks, while auditory and tactile stimuli were presented in front of the participants. Thus, across several tasks, the spatial modulatory effects of audiotactile interactions hardly occur when the auditory stimuli were presented in front of or far from the participants.

In contrast, Kitagawa et al. (2005, Experiment 1) found audiotactile spatial interactions for TOJs. They made participants perform audiotactile TOJs when the tactile stimuli were presented to either the left or right earlobe and auditory stimuli from just behind the participant's head on either the same or the opposite side. The tactile performance was better when the sound was delivered from the same spatial location than when delivered from different spatial locations. Moreover, Kitagawa et al. (2005, Experiment 2) used a speeded left/right tactile discrimination task and showed that the interference effects of auditory stimuli on tactile spatial discrimination were greater when auditory (white noise) distractors were presented from close to the head (20 cm) than far from the head (70 cm). This spatially modulated audiotactile interaction immediately around the head has recently been replicated using different tasks such as a simple detection task (Tajadura-Jiménez et al. 2009) and an audiotactile version of the Colavita effect (i.e., participants' failure to report one modality component of bimodal audiotactile stimuli when being required to report all of the stimulated modalities as soon as possible, Occelli et al. 2010; see also Colavita, 1974, 1982, Occelli et al. 2011). Taken together, auditory stimulation from immediately behind the head is likely to be crucial for spatial modulation of audiotactile interactions.

Another factor that is crucial for spatial modulation of audiotactile interactions is the body part that is stimulated. Tajadura-Jiménez et al. (2009) showed using a simple detection task that the spatial modulation effects occurred for the earlobes but not for the back of the hand placed near the head, which suggests that the surface of the head is a "special" body area for audiotactile interactions. This is the first study to show body part-specific spatial modulation effects of audiotactile interactions in a factorially designed experiment. However, there is a possibility that a different task may make a difference. Spatial crossmodal interactions between auditory and somatosensory modalities may be less apparent in a simple detection task compared to that in other tasks (cf. Kitagawa and Spence 2006). In fact, a simple detection task (Tajadura-Jiménez et al. 2009) and speeded left/right discrimination task (Kitagawa et al. 2005) showed different results in audiotactile interactions. The simple detection task revealed that the spatial modulation effects occurred exclusively when the auditory stimuli were delivered from immediately behind the head. In contrast, in the spatial discrimination task, the spatial modulation effects occurred irrespective of the distance of the auditory stimuli from the center of the participant's head (20 or 70 cm) although greater effects were observed for the stimuli delivered from near the head (20 cm) than those far from the head (70 cm). Furthermore, a study showed that the spatially modulated audiotactile Colavita effect occurred for the hands (fingertips) placed 60 cm away from the trunk as well as the cheeks, as long as a sound was delivered from close to the head (Occelli et al. 2010; see also Occelli et al. 2011 for a review). In this study, we examined whether the spatial modulation effects in audiotactile interactions can be altered in body parts stimulated using a sensitive task; in particular, a speeded left/right discrimination task.

In Experiment 1, tactile stimuli were presented randomly to either left or right cheek, hand (palm or back) placed near the head, and knee, while auditory stimuli were presented to either the same or opposite side from loudspeakers close to the head. The cheek was selected as a surface part of the head consistent with that reported in the study by Occelli et al. (2010, Experiment 2). The back of the hand was examined as a body part different from the surface of the head consistent with that reported in a study by Tajadura-Jiménez et al. (2009). In addition, the palm was selected where an estimated mechanoreceptor density is higher (approximately 70 U/cm^2, Johansson and Vallbo 1979) than the back of the hand (less than 5 U/cm^2, Macefield 1998). Thus, we could manipulate the relative spatial sensitivity of the body parts. During Experiment 1, the hands were always positioned near the head so that the space stimulated was consistent among the cheek, the back of the hand, and the palm. Additionally, the knee was tested as a control because the knees are naturally positioned far from the head. The sensitivity of the knee is reported to be lower than the face and hand (e.g., Rolke et al. 2006), and the proportion of somatosensory cortex devoted to lower limbs is smaller than those for the face and hand (Penfield and Boldrey 1937). The aforementioned studies would predict that the spatial modulation of audiotactile interactions would be most apparent in the cheek among the body parts tested, because the cheek is a surface of the head. However, we found the spatial modulation effects for all body parts stimulated. In Experiment 2, we investigated how the hand position (near or far from the head) and sound position (near or far from the head) affect the spatial modulation effect in audiotactile interactions in the palm and the back of the hand. The hands were placed either near the head or on the knee, while auditory stimuli were delivered either from immediately close to the head or from close to the knee. The results showed that the spatial modulation effects occurred irrespective of the hand position (near or far from the head), sound position (near or far from the head), and body part (palm or the back of the hand) although the magnitude of the effects could be altered by these factors.

Experiment 1

Method

Participants

Eighteen volunteers (eight males and ten females, mean age 21.6 years, ranging from 19 to 27 years) participated in this experiment. All the participants were naive to the purpose of the study. This study followed the tenets of the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of Kumamoto University. Participants gave their informed consent to participate in this study before the start of their experimental sessions.

Apparatus and stimuli

The blindfolded participants sat in a sound-attenuated room. Two air-puff stimulators were used to present the somatosensory stimuli. Air-puffs produced by using compressed air were delivered to either the left or right cheek, hand (palm), hand (back), and knee through a nozzle with external diameter of 3.0 mm and their orifices placed 2 cm from the skin (see also Sekiyama et al. 2012, for further information on the air-puff stimulators). The intensity of the air-puff was clearly suprathreshold (50 ms, 0.1 MPa). To mask completely any noise made by the operation of the air-puff stimulators, a masking stimulus (white noise) was presented continuously at 68 dB(A) throughout the experiment via headphones. We confirmed that no participants heard any operation noise due to the masking noise.

The auditory target stimuli consisted of bursts of white noise (50 ms) and were presented from either the left or right loudspeakers placed 45° to the left and right behind the participants' head. The distance between the loudspeakers and the center of the participant's head was 20 cm. The A-weighted sound pressure level of the auditory target was 90 dB as measured at the participants' ear position. Sample trials before the experiment began verified that the target sounds were clearly audible even when headphones were worn for presentation of masking noise. The time delay from the trigger to the onset of air-puff at the outlet of the nozzle was 50 ms. The delay was compensated by our computer program so that the somatosensory and auditory stimuli were synchronously presented. Foot-pedals were used for registering participants' responses.

Procedure

The stimulated body parts were cheeks, palms, backs of hands, and knees. The hands were placed aside of the cheeks for the hand (palms and backs) conditions. Different body parts were investigated in different blocks. In each block, the air-puff targets were presented randomly to either the left or right side. The auditory distractors were also presented randomly from one of the two loudspeakers on either side. The participants were instructed to make speeded discrimination responses regarding the side (i.e., left versus right) from which the air-puff targets were presented by using two foot-pedals, one situated below each foot. The participants depressed left (right) foot-pedal to indicate the air-puff target was presented from the left (right) side. The participants were instructed to respond as quickly and as accurately as possible and to ignore the auditory stimuli as much as possible. Each participant completed three blocks of 40 practice trials (which were not analyzed), followed by four experimental blocks of 80 trials (two positions of the air-puff targets × two positions of the auditory distractors × 20 trials). In the first practice trials, only auditory stimuli were presented and the participants were required to make auditory left/right discriminations in order to confirm the participants' discriminability of the location of the auditory stimuli. In the second practice trials, the air-puff targets were presented without any distractors to accustom the participants to the air-puff spatial discrimination task, and, then, in the third practice, the air-puff targets were presented with the auditory distractors. The experimental session lasted for approximately 60 min.

Index of audiotactile interaction

To investigate any potential speed–accuracy trade-offs, we calculated "inverse efficiency" (IE) scores. IE scores are a standard way to combine RT and accuracy data into a single performance measure, computed as the median RT divided by the proportion of correct trials for a given condition (Kitagawa et al. 2005). A higher IE value indicates worse performance, just as for RT and error measures. Our use of the IE measure was motivated by the desire to make our results comparable with those reported in previous studies (Kitagawa et al. 2005).

Results and discussion

Trials with an incorrect response were discarded from the analysis of the reaction time (RT) data. Approximately 1.6 % of trials were removed across all participants. Figure 1a, b show the average IE scores for each condition and the mean crossmodal distractor interference scores (calculated as the IE score difference on different minus same-side trials), respectively. Performance on the air-puff spatial discrimination task was slower and less accurate when the auditory distractor was presented on the opposite side to the air-puff target (mean reaction time Mean ± SD = 382 ± 85 ms; mean error rate Mean ± SD = 3.9 ± 5.8 %) than when both stimuli were presented on the same side (mean reaction time 321 ± 73 ms; mean error rate 0.3 ± 1.5 %, see also Table 1 for details). In order to investigate whether the auditory interference effect, represented by the crossmodal distractor interference scores, was modulated by body parts, we analyzed the crossmodal distractor interference scores using a one-way ANOVA with within-participants factor of body part. There was a main effect of body part ($F_{3,51} = 5.10$, $p = .004$, $\eta^2 = 0.144$). A Tukey's post hoc test ($\alpha = 0.05$) revealed higher crossmodal distractor interference scores for the back of the hand than for the other body parts.

Table 1 Median reaction times (in ms), SD, percentage of errors, inverse efficiency scores (median RT/proportion of correct responses, in ms), and mean crossmodal distractor interference effects, as a function of the body part and relative stimulus position in Experiment 1

Body part	Relative stimulus position		Crossmodal distractor interference effect
	Same	Different	
Cheek			
RT (ms) (±SD)	304 (63)	350 (74)	47
Errors (%)	0.0	0.4	0.4
IE	304	358	55
Back of hand			
RT (ms) (±SD)	309 (52)	402 (77)	93
Errors (%)	0.4	3.2	2.9
IE	310	422	112
Palm			
RT (ms) (±SD)	318 (69)	377 (87)	58
Errors (%)	0.4	3.1	2.7
IE	319	390	70
Knee			
RT (ms) (±SD)	351 (96)	399 (97)	48
Errors (%)	1.2	5.8	4.7
IE	354	325	72

Thus, in contrast with the findings reported in a previous study (Tajadura-Jiménez et al. 2009), we observed spatial modulation of audiotactile interactions in any body parts investigated, including the body parts placed far from the head (i.e., the knees). Interestingly, our data did not show priority of the surface of the head in the audiotactile spatial interactions. This suggests that what matters for strong

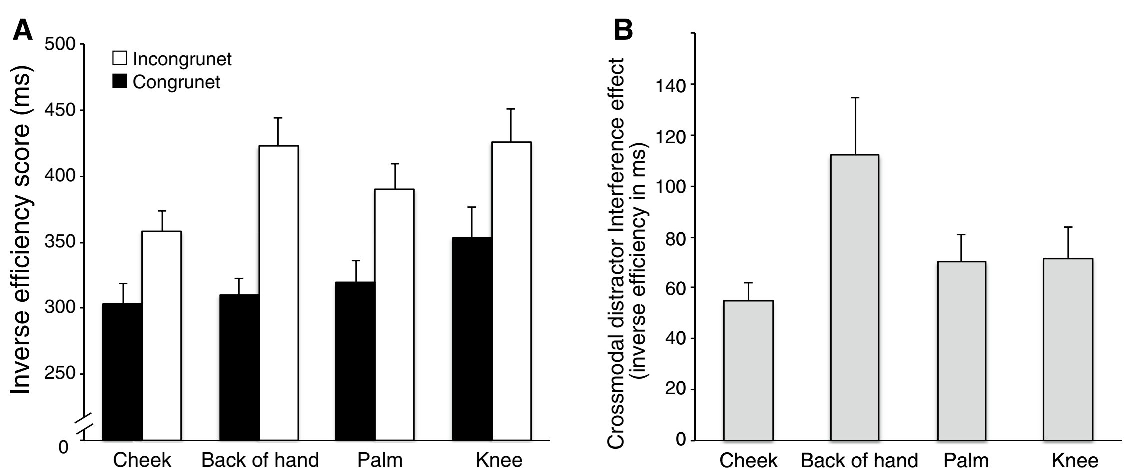

Fig. 1 Results of Experiment 1. **a** Inverse efficiency scores (i.e., median RT/proportion of correct responses) for audiotactile spatial interactions in each body part (cheek, back of the hand, palm, and knee). **b** The crossmodal distractor interference effects measured in terms of inverse efficiency. The *error bars* represent the within-participants SE of mean

audiotactile spatial interactions might be not just whether a stimulated area is a surface of the head.

Experiment 2

Experiment 1 demonstrated that the spatial modulation effects between auditory and somatosensory modalities were observed irrespective of the body parts stimulated (cheek, palm, the back of the hand, and knee). Moreover, higher crossmodal distractor interference scores were obtained for the back of the hand than for the other body parts. Experiment 2 targeted the palm and the back of the hand and investigated how the spatial arrangement between hand position (near or far from the head) and sound position (near or far from the head) affected the spatial modulation effect in audiotactile interactions. The hands were placed either near the head or on the knee, while auditory stimuli were delivered from either close to the head or close to the knee. Occelli et al. (2010, Experiment 2) reported that the spatially modulated audiotactile Colavita effect for the hands occurred more when sounds were presented from headphones than from loudspeakers placed 60 cm away from the trunk. This would predict that presenting sounds near the head is more important for the spatial modulation effect of audiotactile interactions than the distance between a sound source and a body part.

Methods

Participants

Eighteen volunteers (nine males and nine females, mean age 23.5 years, ranging from 21 to 28 years) participated in this experiment. All the participants were naive to the purpose of the study.

Stimuli and procedure

Air-puffs were delivered to either the left or right palm and back of the hand. When stimulated, the hands were placed aside of the cheeks (i.e., near the head) or on the knees (i.e., far from the head). The auditory distractors were presented randomly from one of the two loudspeakers placed 45° to the left and right behind the participant's head (i.e., near the head; 20 cm from the center of the participant's head) or just aside the participants' knees (i.e., far from the head). Thus, we used a 2 (body part: palms and backs of the hands) × 2 (sound position: near and far from the head) × 2 (hand position: near and far from the head) × 2 (spatial congruency of audiotactile stimuli: congruent and incongruent) experimental design. Each participant completed three blocks of 40 practice trials (which were not analyzed) and 8 experimental blocks of 40 trials. The factors of body part, sound and hand positions were blocked, and the order of the blocks was randomized among participants. The experimental session lasted for approximately 90 min. Except for these variations, the experimental set-ups, stimuli, and procedure were the same as those in Experiment 1.

Results and discussion

Trials with an incorrect response were discarded from the analysis of the reaction time (RT) data. Approximately 2.0 % of trials were removed across all participants. Figure 2a, b show the average IE scores for each condition and the mean crossmodal distractor interference scores, respectively. Consistent with the results of Experiment 1, performance on the air-puff spatial discrimination task was slower and less accurate when the auditory distractor was presented on the opposite side to the air-puff target (mean reaction time Mean ± SD = 402 ± 154 ms; mean error rate Mean ± SD = 3.9 ± 4.9 %) than when both stimuli were presented on the same side (mean reaction time Mean ± SD = 354 ± 139 ms; mean error rate Mean ± SD = 0.1 ± 0.7 %, see also Table 2 for details).

The particular interest of the present study was whether the auditory interference effect, represented by the crossmodal distractor interference scores, was modulated by body parts, hand position, or sound position. To elucidate this aspect, we analyzed the crossmodal distractor interference scores using a three-way ANOVA with within-participants factor of body part, hand, and sound positions. All main effects were significant (body part $F_{1,17} = 15.36$, $p = .001$, $\eta^2 = 0.032$; hand position $F_{1,17} = 4.98$, $p = .039$, $\eta^2 = 0.009$; sound position $F_{1,17} = 26.78$, $p < .001$, $\eta^2 = 0.166$), and a two-way interaction between hand and sound positions was significant ($F_{1,17} = 10.59$, $p = .005$, $\eta^2 = 0.023$). Because a three-way interaction was also significant ($F_{1,17} = 9.13$, $p = .008$, $\eta^2 = 0.011$), tests for simple effects were performed. The sounds delivered from near the head caused larger crossmodal distractor interference effects than those delivered from far from the head for all combinations of body part with hand position ($Fs_{1,17} > 12.89$, $ps < .002$, $\eta^2 s > 0.128$) except for the condition where the back of the hand placed far from the head was stimulated ($F_{1,17} = 2.31$, $p = .147$, $\eta^2 = 0.046$). A simple main effect of hand position was also pronounced when the back of the hand was stimulated, while sounds were delivered from near the head ($F_{1,17} = 52.93$, $p < .001$, $\eta^2 = 0.084$): the effect was larger when the hands were placed near the head than far from the head. Furthermore, the crossmodal distractor interference was larger for the back of the hand than the palm when the sounds

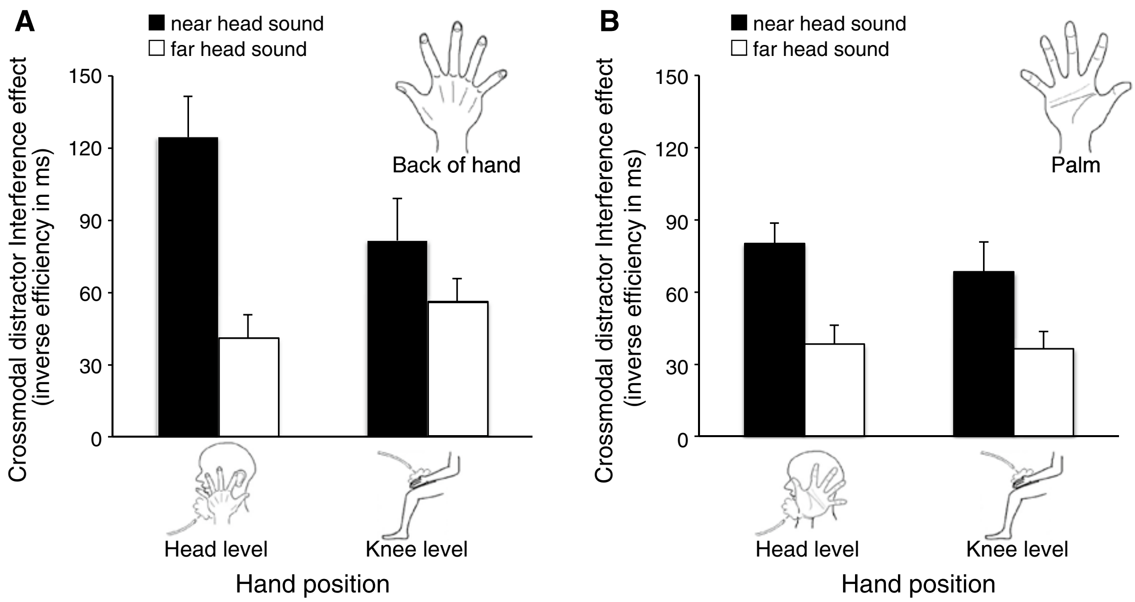

Fig. 2 Results of Experiment 2. **a** The crossmodal distractor interference effects for the back of the hand, measured in terms of inverse efficiency as a function of the hand position (near/far from head) and the sound position (near/far from the head). **b** The crossmodal distractor interference effects for the palm, measured in terms of inverse efficiency as a function of the hand position (near/far from head) and the sound position (near/far from the head). The *error bars* represent the within-participants SE of mean

were placed near the hand (near the head $F_{1,17} = 11.19$, $p = .004$, $\eta^2 = 0.137$; far from the head $F_{1,17} = 10.69$, $p = .005$, $\eta^2 = 0.074$). This is consistent with Experiment 1, where the crossmodal distractor interference scores were higher for the back of the hand than for the palm.

General discussion

The present study investigated whether audiotactile crossmodal spatial interactions can be altered depending on stimulated body parts and the spatial relationship between sounds and the body parts. Experiment 1 demonstrated the spatial modulation of audiotactile interactions in any body parts stimulated (cheek, back of the hand, palm, and knee) when sounds were presented from close to the head. Experiment 2 showed that the spatial modulation effects of audiotactile interactions were observed irrespective of the stimulated body part (palm/back), hand position (near/far from the head), and sound position (near/far from the head). As measured by the magnitude of the spatial modulation effects, the effects were more pronounced for the sounds delivered from near the head than far from the head. The effects of body parts were also observed when the hands and sounds were placed in proximity: the spatial modulation effects were larger for the back of the hand than for the palm. Additionally, there was an effect of hand position: the spatial modulation effects for the back of the hand were larger when the hands were placed near the head than far from the head as long as the sounds were placed near the head.

Several previous studies have already shown the spatial modulation effects of audiotactile interactions for auditory stimuli originating from the space close to the head with a variety of tasks or measures such as TOJs (Kitagawa et al. 2005), speeded left/right discrimination (Kitagawa et al. 2005), simple detection (Tajadura-Jiménez et al. 2009), and speeded modality detection/discrimination (Occelli et al. 2010). A neurophysiological study showed that monkeys' neurons in the ventral premotor cortex responding to tactile stimulation on the sides and back of the head also responded to auditory stimuli delivered from close to the head. The modulatory effects of auditory stimuli on these tactile neurons were weak or disappeared as the distance of the auditory stimuli from the head increased (Graziano et al. (1999), but see also Moore and King (1999)'s commentary). Also, a neuropsychological study demonstrated that tactile extinction in brain-damaged patients was enhanced by auditory stimuli presented from close to the head (20 cm), but not far from the head (Farnè and Làdavas 2002). The results of our current study provide further support for the specificity of the peri-head space for audiotactile spatial interactions. It should be noted that sound distance manipulation also causes changes in interaural intensity difference (i.e., near sounds are more lateralized than far sounds due to the head acting as an acoustic shield). The previous studies as well as the present study did not investigate which acoustic cues are crucial for the

Table 2 Median reaction times (in ms), standard deviation, percentage of errors, inverse efficiency scores (median RT/proportion of correct responses, in ms), and mean crossmodal distractor interference effects, as a function of the body part and relative stimulus position in Experiment 2

Body part	Hand position	Sound distance	Relative stimulus position: Same	Relative stimulus position: Different	Crossmodal distractor interference effect
Back of hand	Near the head	Near			
		RT (ms) (±SD)	362 (122)	435 (136)	73
		Errors (%)	0.3	9.6	9.3
		IE	363	487	124
		Far			
		RT (ms) (±SD)	372 (128)	401 (142)	29
		Errors (%)	0.0	3.1	3.1
		IE	372	413	41
	Far from the head	Near			
		RT (ms) (±SD)	370 (156)	432 (182)	62
		Errors (%)	0.3	3.9	3.6
		IE	371	452	81
		Far			
		RT (ms) (±SD)	389 (192)	433 (198)	44
		Errors (%)	0.0	3.1	3.1
		IE	389	445	56
Palm	Near the head	Near			
		RT (ms) (±SD)	336 (122)	397 (127)	61
		Errors (%)	0.0	4.5	4.5
		IE	336	415	79
		Far			
		RT (ms) (±SD)	319 (102)	350 (119)	31
		Errors (%)	0.0	1.7	1.7
		IE	319	357	38
	Far from the head	Near			
		RT (ms) (±SD)	334 (93)	388 (127)	54
		Errors (%)	0.3	4.2	3.9
		IE	335	404	69
		Far			
		RT (ms) (±SD)	351 (181)	382 (192)	31
		Errors (%)	0.0	1.7	1.7
		IE	351	388	37

distance-dependent audiotactile interactions. In the present study, in particular, spectral cues and HRTF (head-related transfer function) parallax normally available for auditory distance perception were not useful because the headphones were used to mask noise made by the operation of the air-puff stimulators. Moreover, the sound pressure level of auditory stimuli delivered from loudspeakers was always 90 dB at the participants' head center and ear height, irrespective of loudspeaker position. Nevertheless, almost the same results as the previous studies were observed. This suggests a possibility that more lateralized sounds (i.e., near sounds) lead to more interference of left/right discrimination.

A crucial finding of the present study is that the audiotactile spatial interactions were not limited to the surface of the head. The interactions occurred beyond the space close to the head, and, furthermore, occurred when the auditory stimuli were delivered from far from the head, although the effect size was altered in body part, the space where the body part was placed or the space where the auditory stimuli were presented. These are inconsistent with any previous studies aforementioned. For example, Tajadura-Jiménez et al. (2009) showed that the spatial modulation effects were specific to the surface of the head. Neurophysiological studies (Fu et al. 2003; Menning et al. 2005) also revealed that audiotactile interactions were pronounced when the head or face was stimulated, but not when the hand was stimulated. Also, regarding the space where audiotactile spatial interactions occur, most previous studies reported that the audiotactile spatial interactions were not salient when the auditory stimuli were presented in frontal space (Lloyd et al. 2003; Murray et al. 2005; Zampini et al. 2005a, b, 2007) or in the space far from the head (Occelli et al. 2010; Tajadura-Jiménez et al. 2009).

One explanation for these inconsistencies is a difference in task. Tajadura-Jiménez et al. (2009), Murray et al. (2005) and Zampini et al. (2005a, b) used simple detection tasks, which have been argued to be far less sensitive to multisensory interactions related to attentional cueing than discrimination tasks (cf. Kitagawa and Spence 2006). Indeed, Kitagawa et al. (2005) reported, by using a speeded left/right discrimination task, that the crossmodal distractor interference effects occurred irrespective of the distance of the auditory stimuli from the center of the participant's head (20 or 70 cm), although the effects were larger for the sounds delivered from near the head (20 cm) than far from the head (70 cm). Therefore, use of a speeded left/right discrimination task in the present study might make audiotactile spatial interaction more pronounced than the previous studies. Regrettably, however, this explanation cannot fully account for the results of Lloyd et al. (2003), in which they showed very weak audiotactile crossmodal links in sustained endogenous covert spatial attention in the space in front of participants even using a speeded spatial discrimination task. Although it is difficult to specify the reasons since there are, in a strict sense, several differences in experimental procedure (e.g., task and stimulated body parts) between Lloyd et al. (2003) and ours, endogenous spatial attention manipulated by Lloyd et al. (2003) may have different effects on audiotactile interactions.

There are at least 3 potential causes of the auditory interference effects on tactile discrimination (cf. Shore et al. 2006): crossmodal exogenous attention, ventriloquism effect, and response conflict. These might also explain why the speeded tactile discrimination task is more sensitive to audiotactile interactions than the other tasks. According to the crossmodal exogenous attention account, the presentation of the auditory distractor captures exogenous attention of the participants to the distractor side, which results in slower responses in the incongruent than in congruent trials. Thus, the above factor suggests a close link in exogenous attention between auditory and tactile modalities (e.g., Spence et al. 1998). In the ventriloquism effect account, the auditory distractor captures the location of the tactile stimuli, which results in more errors and greater reaction times for the incongruent than for the congruent trials. Thus, this factor would involve some form of crossmodal perceptual interaction between the auditory and tactile stimuli, although, to the best of our knowledge, no study has yet reported direct evidence for auditory capture of tactile locations. According to the response conflict account, auditory stimuli prime the appropriate manual responses (e.g., Simon 1990; Simon et al. 1970). Thus, presentation of a distractor could prime a response to that side, which causes response competition between the response tendencies elicited by the auditory and tactile stimuli in the incongruent trials. This would suggest that audiotactile interactions occur at a response selection level. It should be noted that these explanations are by no means exclusive. In fact, we think all the above factors could influence our current findings to some extent. Although it might be feasible to tease these accounts apart by manipulating stimulus onset asynchronies between auditory distractors and tactile targets, as shown in visuotactile interactions by Shore et al. (2006), this is beyond the scope of the present study.

Given these possible underlying mechanisms involved in the task, there is not so much of a difference between the results of Tajadura-Jiménez et al. (2009) and ours. Specifically, spatially modulated audiotactile interactions in the space and body surface around the head might be so strong as to be detected by a variety of tasks (because of the specificity of the peri-head space for audiotactile spatial interactions). Alternatively, the audiotactile interactions beyond the peri-head space might be weaker than those around the head so that they need a more sensitive task to be detected.

It is worth noting a difference in tactile stimulation between the previous studies and ours. Whereas the previous studies used either electric shock or vibration as tactile stimulators, the present study used air-puffs. Most researchers argue that (light) touch, (deep) pressure, pain, and temperature (hot and cold) are differentially processed in the tactile system. Mechanoreceptors are responsible for touch and pressure, whereas nociceptors and thermoreceptors are responsible for pain and temperature, respectively. Moreover, four types of mechanoreceptors (Meissner, Merkel, Pacini, and Ruffini-like endings) located in different layers in the skin differentially contribute to the sense of touch and pressure. Considering these facts, different tactile stimulators are likely to tap different sensors. Vibrotactile stimulators stimulate sensors for both touch and pressure; electrocutaneous stimulators stimulate sensors for both touch and more or less pain. In contrast, air-puffs mainly stimulate sensors for touch because air-puffs do not induce large physical deformation of the surface of the skin different from vibrotactile stimulators. Almost consistent with this consideration, several physiological studies have reported that electric stimuli unspecifically activate deep and superficial receptors and vibration stimulates muscle and joint receptors as well as cutaneous mechanoreceptors because it induces slight movements (Forss et al. 1994; Hashimoto et al. 1988). In contrast, air-puff stimulation can activate rapidly adapting cutaneous mechanoreceptors (Gardner et al. 1984; Schieppati and Ducati 1984). These differences among tactile stimulations might lead to different results.

The results of Experiment 2 showed larger audiotactile spatial interactions for the back of the hand than for the palm when the hands and sounds were positioned in proximity. The effect of the hand position was also pronounced only for the back of the hand when the sounds were placed near the head. Experiment 1, moreover, showed that the crossmodal distractor interference scores were higher for the back of the hand than for the palm (and the cheek and knee). The back of the hand placed near the head was previously tested by Tajadura-Jiménez et al. (2009), but no audiotactile interaction was reported. A difference in (spatial) sensitivity or the number of receptors can be an explanation for this inconsistency. An estimated mechanoreceptor density is higher for the palm (approximately 70 U/cm^2, Johansson and Vallbo 1979) than the back of the hand (less than 5 U/cm^2, Macefield 1998). Several studies have already shown pronounced influences of different sensory modality when information of the given modality is ambiguous or unreliable (e.g., Alais and Burr 2004; Ernst and Banks 2002). Therefore, the audiotactile spatial interactions might be more salient for the back of the hand than for the palm, and the effect of hand position might be apparent only for the back of the hand. It should be noted that the greater auditory influence for the back of the hand was pronounced only when the hands and sounds were positioned in proximity. Serino et al. (2007) have reported that audiotactile interactions for the hands occur only around the hands (peri-hand space) and the space expands by tool use. Thus, these findings suggest that the distance between a body part and auditory stimuli is also important for strong audiotactile spatial interactions as well as body parts stimulated. This might also explain why audiotactile spatial interactions were less pronounced for the knee than the back of the hand in Experiment 1 in spite of lower sensitivity for the knee than the face and hand (e.g., Rolke et al. 2006) and the lower proportion of somatosensory cortex devoted to lower limbs than those for face and hand (Penfield and Boldrey 1937).

Additionally, placing the back of the hand to the cheek is biomechanically unnatural so that this unnatural hand posture might interfere with the audiotactile spatial interactions somehow. It is well known that the postural changes of the arm or the hand could alter perceptual judgments (e.g., Yamamoto and Kitazawa 2001), tactile discrimination (Zampini et al. 2005b), and visuotactile interactions (Igarashi et al. 2010). These should be further investigated in future studies.

In conclusion, these results suggest that the spatial modulation of audiotactile interactions can occur beyond the space and body surface around the head. Air-puff stimulation and a left/right tactile discrimination task have great potential to further elucidate various aspects of spatial modulation effects of audiotactile interactions.

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