BRAIN RESEARCH 1213 (2008) 111–119

available at www.sciencedirect.com

www.elsevier.com/locate/brainres

BRAIN RESEARCH

Research Report

Tactile and visual distractors induce change blindness for tactile stimuli presented on the fingertips

Malika Auvray[a,b,*], *Alberto Gallace*[a,c], *Jess Hartcher-O'Brien*[a],
Hong Z. Tan[d], *Charles Spence*[a]

[a]*Department of Experimental Psychology, Oxford University, Oxford, UK*
[b]*Laboratory of Neurophysics and Physiology, CNRS UMR 8119, Paris, France*
[c]*Dipartimento di Psicologia, Universita' degli Studi di Milano Bicocca, Milano, Italy*
[d]*Haptic Interface Research Laboratory, Purdue University, West Lafayette, USA*

ARTICLE INFO

Article history:
Accepted 9 March 2008
Available online 20 March 2008

Keywords:
Change blindness
Touch
Spatial perception
Attention
Multisensory

ABSTRACT

Recent studies of change detection have revealed that people are surprisingly poor at detecting changes between two consecutively-presented scenes, when they are separated by a distractor that masks the transients typically associated with change. This failure, known as 'change blindness', has been reported within vision, audition, and touch. In the three experiments reported here, we investigated people's ability to detect the change between two patterns of tactile stimuli presented to their fingertips. The two to-be-compared patterns were presented either consecutively, separated by an empty interval or else by a tactile, visual, or auditory mask. Participants' performance was impaired when an empty interval was inserted between the two consecutively-presented patterns as compared with the consecutive stimulus presentation. Participants' performance was further impaired not only when a tactile mask was introduced between the two to-be-compared displays, but also when a visual mask was used instead. Interestingly, however, the addition of an auditory mask to an empty interval did not have any effect on participants' performance. These results are discussed in relation to the multisensory/amodal nature of spatial attention.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

Studies of change blindness have revealed the striking inability of people to detect changes between two consecutively-presented scenes when they are separated by a distractor that masks the transients that would normally be associated with change. Change blindness has been reported to occur under many different conditions in vision (e.g., Auvray and O'Regan, 2003; Irwin, 1991; Levin and Simons, 1997; O'Regan et al., 2000; Rensink et al., 1997; Simons, 1996; Simons et al., 2000). Change blindness has also been reported to occur within the auditory modality, where the phenomenon has been named change deafness (e.g., Chan and Spence, submitted for publication; Eramudugolla et al., 2005; Vitevitch, 2003 although see Demany et al., 2008), as well as within the tactile modality (Gallace et al., 2006b, 2007).

Much of this now large body of empirical research has involved the use of a common experimental technique: namely, impairing people's awareness of the transient signals that normally accompany change. The results obtained using

---

[*] *Corresponding author.* Laboratory of Neurophysics and Physiology, CNRS UMR 8119, Centre universitaire des Saints Pères, 45 rue des Saint Pères, 75270 Paris cedex 06, France.
E-mail address: malika@malika-auvray.com (M. Auvray).

0006-8993/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.brainres.2008.03.015

this kind of change blindness paradigm have been taken by some researchers to suggest that attention is needed for successful change detection, with change blindness occurring whenever the accompanying transient signals fail to draw attention to the location of the change (Simons and Rensink, 2005). When attention is no longer directed to the location of the change, observers have to rely on their memory of the scene in order to infer what may have changed. In this case, changes will tend to be noticed more rapidly if they occur at locations which are likely to attract attention because they are somehow “interesting” to the observer (Rensink et al., 1997). In addition, the right parietal cortex, known to be involved in visual awareness, has been shown to be involved in the detection of visual changes in position in studies involving patients with parietal lesions in the right hemisphere (Pisella et al., 2004), studies involving transcranial magnetic stimulation (Beck et al., 2006), and event-related potential (ERP) studies (Koivisto and Revonsuo, 2006).

The finding that change blindness can be elicited unimodally within vision, within audition, and within touch raises the question of whether similar mechanisms contribute to the change blindness effect observed within the various different sensory modalities. Relevant to this issue are the results of a functional magnetic-resonance imaging (fMRI) study reported by Downar and his colleagues (Downar et al., 2000). This study of unimodal auditory, visual, and tactile change detection revealed the existence of a distributed cortical network involved in the detection of sensory changes in the environment, having both modality-specific and multisensory components. In particular, brain regions responsive to stimulus change included putatively-unimodal areas such as the visual, auditory, and somatosensory cortices (cf. Ghazanfar and Schroeder, 2006), as well as multimodally-responsive areas, comprising a right-lateralized network including the temporoparietal junction, inferior frontal gyrus, insula, and the supplementary motor areas. These results suggest that at least certain of the processes underlying the detection of change in the environment are multisensory/amodal in nature.

The experimental studies described thus far have shown that distractors presented within the same sensory modality as the change can elicit change blindness. Recent research by Gallace, Auvray, Tan, and Spence (2006a) has demonstrated that people’s ability to detect the presence of positional changes between two patterns of tactile stimuli presented on the body surface is impaired not only when tactile distractors are used to mask the change, but also when visual distractors are used instead. This finding therefore suggests that the transients used to elicit change blindness do not necessarily have to occur within the same sensory modality as the change; presumably because their primary role is to attract attention away from the transients generated by the change itself, and cross-modal cues can be just as effective as intramodal cues in this regard (see Spence et al., 2004).

The experimental studies of tactile change blindness reported above were performed with the tactile stimuli presented on the participants’ body surface. The question therefore arises as to whether change blindness would also have occurred if the tactile stimuli were presented on the participants’ fingers. Indeed, given the fact that the proportion of the somatosensory cortex devoted to the representation of the hands is larger than that devoted to the representation of other body parts (e.g., Nakamura et al., 1998; Narici et al., 1991), one might readily expect differences in the duration and/or capacity of short term representations of stimuli presented on the finger versus on the rest of the body surface (see Gallace and Spence, 2008, submitted for publication; Gallace et al., in press). These longer lasting representations of stimuli presented on the fingers, by reducing the cognitive (and/or attentional) load involved in the task might therefore improve participants’ performance (see Cartwright-Finch and Lavie, 2007; Lavie, 2006). In other words, an enhanced ability to process tactile stimuli when presented on the fingers (rather than on the rest of the body surface) might result in people being less impaired in detecting changes when a mask or an empty interval is introduced between the two tactile displays. The first aim of the present study was therefore to investigate whether change blindness would be elicited when the two to-be-compared tactile displays were presented on the participants’ fingers.

In addition, it has been suggested that the information that is available to one sensory modality will dominate that available to another if it carries a lower level of variance for a specific task (see Ernst and Banks, 2002; Ernst and Bülthoff, 2004). Previous studies have shown that visual masks impair the detection of changes between tactile stimuli presented across the body surface. However, the accuracy for tactile change detection might be higher for tactile stimuli presented on the hand versus on the rest of the body surface. Thus, it might be the case that tactile change detection for stimuli presented on the hands is accurate enough that masks presented in another sensory modality would not have a detrimental effect on performance. Thus, the second aim of the experiments reported here was to compare the influence of tactile, visual, and auditory masks on the detection of changes between two tactile displays presented on the fingertips.

It should be noted that although the interactions between audition and touch have been documented using a variety of techniques including magnetoencephalography (e.g., Menning et al., 2005; see Kitagawa and Spence, 2006, for a recent review), these interactions have never been investigated before using the paradigm of change blindness. Our hypothesis, given the existence of extensive cross-modal links in spatial attention and in general in spatial processing and representation (e.g., see Spence et al., 2004, for a review), was that tactile change blindness should be elicited, not only when tactile stimuli are used to mask the change, but also when visual and auditory distractors were introduced between the two to-be-compared tactile displays.

Therefore, in the three experiments reported here, we investigated change detection performance for pairs of tactile patterns presented on the participants’ fingers. The two to-be-compared displays consisted of 3 tactile stimuli that could be presented either consecutively, separated by an empty interval of 150 ms, or else separated by a masked interval of the same duration. The first experiment compared participants’ performance when the tactile patterns were presented consecutively, separated by an empty interval, or separated by a tactile mask. The second experiment compared participants’ performance when the two to-be compared patterns of tactile stimuli were separated by an empty interval, by a tactile mask, by a visual mask, or by an auditory mask. The third and final experiment further investigated the influence of the spatial congruency between the tactile pattern and the auditory mask on change detection performance.

2. Results

2.1. *Experiment 1*

In the first experiment, we investigated the ability of participants to detect changes between two patterns of 3 tactile stimuli presented on their fingers. The two to-be-compared patterns could be presented consecutively, separated by an empty interval, or else separated by a tactile mask.

Trials in which the participants failed to make a response before the trial was terminated (<1% of trials overall) were not included in the data analyses. The percentages of correct and erroneous change detection responses were used to calculate a measure of perceptual sensitivity (d′) and response bias (β) for each participant and block type using signal detection theory (e.g., Macmillan and Creelman, 2004; see Fig. 1). An ANOVA conducted on the d′ and β data with the factor Block type (no interval, empty interval, and tactile mask) revealed a significant main effect on d′ [$F(2,22)=79.22$, $p<.0001$] and on β [$F(2,22)=5.30$, $p<.05$]. A Duncan post-hoc test on the d′ data revealed significant differences in performance between all 3 block types (all $ps<.01$). The sensitivity of participants' perceptual judgments was higher in the no interval block (mean: 3.2±0.14 S.E.), followed by the empty interval block (mean: 1.9±0.15), and then the tactile mask block (mean: 1.1±0.13).

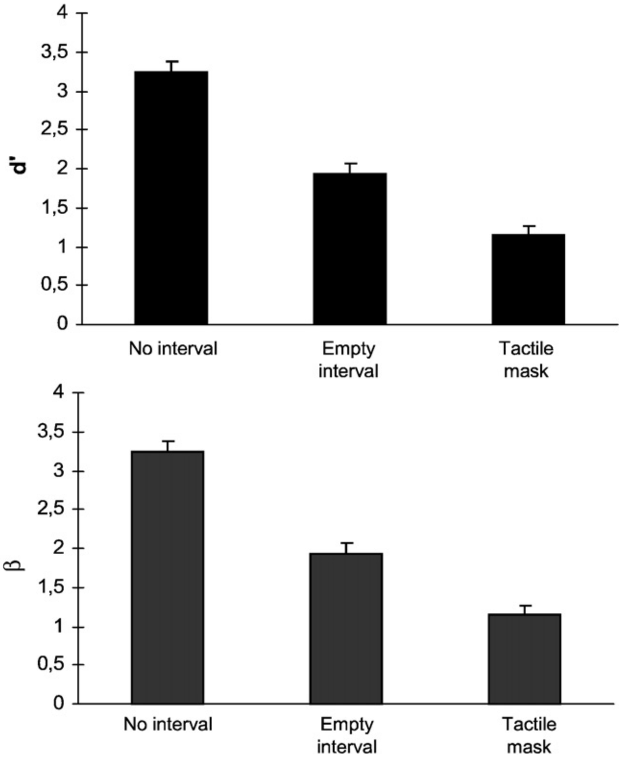

Fig. 1 – Participants' mean performance (d' and β) for the 3 conditions tested in Experiment 1: no interval, empty interval, and tactile mask. The error bars represent the standard error of the means.

A Duncan post-hoc test on the Block type factor revealed a marginal difference between the empty interval and the tactile mask blocks ($p=.06$). In order to determine the direction of the bias, an ANOVA was conducted on the raw error data with 2 factors: Block type (no interval, empty interval, and tactile mask) and Presence versus absence of change between the 2 patterns of stimuli composing the displays. The analysis revealed a significant main effect of the Presence versus absence of change [$F(1,11)=19{,}52$, $p<.01$], a significant effect of Block type [$F(2,22)=79{,}47$, $p<.0001$], and a significant interaction between these two factors [$F(2,22)=5{,}61$, $p<.05$]. A Duncan post-hoc test revealed that the participants made significantly more errors when there was a change than when there was no change in the empty interval and tactile mask conditions (both $ps<.001$) but not in the no interval condition. This result is similar to the results obtained in previous studies of change blindness (e.g., Auvray et al., 2007; Gallace et al., 2006b) where participants' errors reflected their failure to perceive that a change had occurred, rather than a tendency to report changes that had not, in fact, occurred. Furthermore, participants' performance was very high in the no interval condition for both the change and no change conditions (7.3% and 3.5% of errors, respectively). Thus, the lack of effect of the presence versus absence of a change in the no interval condition can be explained by this ceiling effect on performance.

The results of Experiment 1 revealed that participants' performance in detecting changes in position was impaired by the introduction of both an empty interval and a tactile mask between the two consecutively-presented tactile displays. We thus showed, for the first time, that a change blindness effect can be elicited when the two to-be-compared stimulus patterns are displayed on participants' fingertips. It should be noted that the differences in the experimental designs make it difficult to directly compare our results to those obtained by Gallace et al. (2006b) in which the stimuli were presented across the participants' body surface instead. Furthermore, in their experiments, the tactile patterns were presented for 200 ms and the empty and masked intervals lasted 110 ms while in our experiment the tactile patterns were presented for 600 ms and the empty and masked intervals lasted 150 ms. With this difference in mind, it should be noted that the participants' perceptual sensitivity in the study of Gallace et al. (2006b) for the 3 conditions of stimulus presentations was 4, 3.5, and 1.4; whereas in the experiment reported here the perceptual sensitivity was 3.2, 1.9, and 1.1 (for the no interval, empty interval, and tactile mask conditions, respectively). What can be inferred from these results is that a change blindness effect can be obtained no matter what locations on the body the stimuli are presented from (i.e., on the fingers vs. on the rest of the body).

2.2. *Experiment 2*

In our second experiment, we investigated tactile change detection performance when the two to-be-compared patterns of stimulation were separated by an empty interval, by a tactile mask, by a visual mask, or by an auditory mask.

Trials in which the participants failed to make a response before the trial was terminated (<1% of trials overall) were not included in the data analyses. An ANOVA conducted on the d' and β data with the factor Block type (empty interval, tactile mask, visual mask, and auditory mask) revealed a significant main effect on d' [$F(3,33)=29.44$, $p<.0001$] and on β [$F(3,33)=8.4$, $p<.05$]. A Duncan post-hoc test on the d' data revealed a significant difference in sensitivity between all block types (all $ps<.01$) except between the empty interval and the auditory mask blocks. The sensitivity of participants' perceptual judgments was higher in the empty interval block (mean: 2.3 ± 0.18 S.E.) and the auditory mask block (mean: 2.2 ± 0.18), followed by the visual mask block (mean: 1.9 ± 0.20), and lowest in the tactile mask block (mean: 1.4 ± 0.20) (see Fig. 2).

A Duncan post-hoc test on β revealed a significant difference between the empty interval and the tactile mask blocks ($p<.05$) and between the tactile mask and the auditory mask blocks ($p<.01$). An ANOVA was conducted on the raw error data with 2 factors: Block type (empty interval, auditory mask, visual mask, and tactile mask) and Presence versus absence of change between the 2 patterns of stimuli composing the displays. The analysis revealed a significant main effect of the Presence versus absence of change [$F(1,11)=53{,}32$, $p<.01$], a significant effect of Block type [$F(3,33)=31{,}19$, $p<.0001$], and a marginally-significant interaction between these two factors [$F(3,33)=2{,}79$, $p=.056$]. A Duncan post-hoc test revealed that the participants made significantly more errors when there was a change than when there was no change in all the conditions of stimulus presentation (all $ps<.001$).

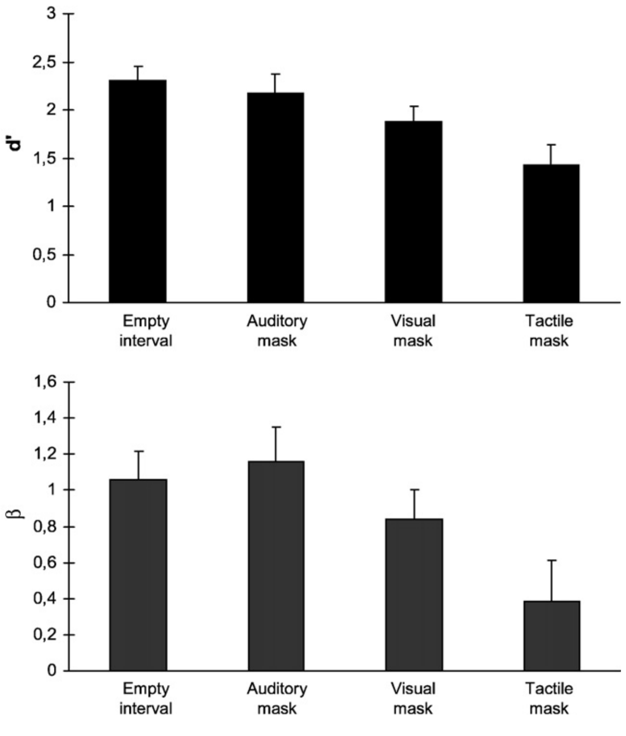

Fig. 2 – Participants' mean performance (d' and β) for the 4 conditions tested in Experiment 2: empty interval, auditory mask, visual mask, and tactile mask. The error bars represent the standard error of the means.

An additional analysis was performed in order to assess the influence of the spatial congruency between the side of the participant's body from where the mask was presented and the side where the change occurred. The change in position between the two to-be-compared patterns could occur on the participant's left or right (note that changes in position always occur within the same hand). Similarly, the tactile and visual masks could be displayed on the participants' left or right hand and the auditory mask could be presented on the left or right side. An ANOVA was conducted on the raw error data for those trials in which there was a change in position between the two to-be-compared displays with 2 factors: Block type (tactile mask, visual mask, and auditory mask) and Congruency between the side of the change (i.e., right hand vs. left hand) and the side of the mask (congruent vs. incongruent). The analysis did not reveal any main effect of Congruency [$F(1,11)<1$, *ns*], nor any interaction between Congruency and Block type [$F(2,22)<1$, *ns*].

The results of our second experiment therefore revealed that participants' performance in detecting changes in position between two tactile displays was impaired when a mask, either tactile or visual, was introduced between the two to-be-compared displays as compared with the empty interval condition. Interestingly, however, the presentation of an auditory mask did not have a deleterious effect on participants' performance above and beyond that of the empty interval. It might be argued that the absence of any effect of the auditory mask can be accounted for by the fact that it was not presented from the same spatial locations as the tactile stimuli (see Ho et al., submitted for publication, on this point). Indeed, in our experiments, both the tactile stimuli and the visual and tactile masks were presented on the participant's fingers whereas the auditory stimuli were presented from in front of the participants (at a distance of 25 cm from the participant's body midline), via loudspeaker cones. One could therefore argue that a mask might impair the detection of positional changes between two stimulus displays presented in another sensory modality only when there is a spatial congruency between the position of the masks and that of the tactile stimuli. It is worth noting that the results of the additional data analyses do not point toward that hypothesis: That is, the congruency between the sides where the tactile change and the mask were presented (no matter whether the mask was auditory, visual, or tactile) was not found to affect the performance of our participants.

Moreover, it should also be noted that previous studies using similar non-coincident conditions of stimulus presentation (e.g., tactile stimuli presented on the participants' hands, and auditory stimuli presented via headphones) have shown the existence of audio-tactile interactions in previous research (e.g., Guest et al., 2002; Jousmäki and Hari, 1998). In addition, some other studies have suggested that the effect of the spatial co-location between auditory and tactile stimuli on the nature and magnitude of audio-tactile interactions might be weak or non-existent (e.g., Lloyd et al., 2003; Murray et al., 2005; Zampini et al., 2007). For example, Lloyd et al. (2003) reported that the effect of auditory distractors on a task involving the discrimination of the elevation of vibrotactile target stimuli presented on their hands was larger when the auditory distractors were presented from the same side as the vibrotactile targets than when they were presented from the opposite side. However, the effect of the auditory distractors was not modulated by the relative position of the hands with respect to the loudspeakers presenting the auditory distractors. The results of these studies therefore suggest the existence of cross-modal links between audition and touch that can be independent of any spatial coincidence. However, we attempted to more effectively rule out the possibility that the distance from which the auditory mask was presented was the reason why the auditory mask did not give rise to tactile change detection performance in Experiment 2. To do so, a final experiment was conducted in which the auditory mask was presented from a loudspeaker cone that was now placed directly below the participants' fingers.

2.3. *Experiment 3*

In the third experiment, we investigated the influence of the spatial congruency between the tactile pattern and the auditory mask on change detection performance. The two to-be-compared patterns of 3 tactile stimuli were separated by an auditory mask that was displayed from either of two loudspeakers above which the participants rested their hands.

Trials in which the participants failed to make a response before the trial was terminated (17% of trials overall) were not included in the data analyses. An ANOVA conducted on the d' and β data with the factor Mask (mask under the hand which received 2 stimuli vs. under the hand that received just 1 stimulus) did not reveal any significant effect on d' [$F(1,13)=2.66$, $p=.13$] or β [$F(1,13)<1$, *ns*].

An additional ANOVA was performed on the raw error data on the trials in which there was a change in position between the two to-be-compared displays with 2 factors: Number (change on the hand that received one stimulus vs. change on the hand that received 2 stimuli) and Spatial congruency (the auditory mask was displayed under the hand where the change occurred vs. under the other hand). The analysis did not reveal any effect of Number [$F(1,13)<1$, *ns*], nor any effect of Spatial congruency [$F(1, 13)<1$, *ns*], nor any interaction between these two factors [$F(1,13)=3.17$, $p=.10$].

The results of Experiment 3 revealed that when the tactile pattern and the auditory mask were presented from the same locations (on and under the participants' fingers, respectively), the influence of the auditory mask on participants' performance was the same no matter whether or not it was presented from the same side as the change or from the opposite side. This result suggests that, in the case of change detection, the spatial congruency between the sides from which the tactile change and the mask were presented do not affect the magnitude of audio-tactile interactions.

3. Discussion

The three experiments in the study reported here were designed to investigate participants' ability to detect changes in position taking place between two tactile patterns presented on their fingers. Experiment 1 compared the ability of participants to detect the presence of positional changes between the two tactile patterns when these two patterns were presented consecutively, separated by an empty interval, or by a tactile mask of similar duration. Experiment 2 compared participants' performance when the two to-be-compared tactile patterns were separated by an empty interval, or by a tactile, visual, or auditory mask. Experiment 3 further investigated the influence of the spatial congruency between the auditory mask and changes in the tactile display under conditions in which both were presented from close to the participants' hands.

The main result to emerge from the analysis of the results of Experiment 1 was that change blindness was elicited when an empty interval was inserted between the two to-be-compared patterns (as compared to the condition in which the stimuli were presented continuously on the participants' skin). In addition, participants' performance was further impaired when a tactile mask was introduced between the two to-be-compared displays. It should be noted that the change blindness effect obtained in the empty interval and tactile mask conditions might be seen as the tactile analog of the visual change blindness effect obtained via the insertion of a blank screen (e.g., Rensink et al., 1997) and via the insertion of visual "mudsplashes" (e.g., O'Regan et al., 1999) between two to-be-compared visual displays, respectively. We were thus able to replicate the results recently reported by Gallace and his colleagues (Gallace et al., 2006b, in press) where tactile change blindness was demonstrated when the stimulus displays were presented on participants' body.

The main result to emerge from the analysis of the results of Experiment 2 was that participants' performance was impaired by both the introduction of tactile and visual masks as compared with the empty interval condition. This result further highlights the similarities between the change blindness phenomenon reported previously within vision, audition, and touch. The possibility of eliciting tactile change blindness by means of the presentation of visual distractors provides behavioral support for the view that certain of the processes underlying the detection of changes are multisensory/amodal in nature (Downar et al., 2000). These results might also be taken to support the view that spatial attention is controlled cross-modally (e.g., Spence and Driver, 2004) which is consistent with claims that human attentional resources are not used to process information in an entirely separate, or modality-specific, manner, but rather, processing resources are considered to be shared among vision, touch, and audition. In particular, the sudden presentation of a stimulus in one sensory modality (e.g., touch) appears capable of exogenously capturing a person's attention in such a way that the processing of stimuli presented in other sensory modalities (e.g., vision or audition) at the same location is facilitated (see Spence et al., 2004, for a review).

In the study reported here, the presentation of a tactile mask between the two to-be-compared tactile displays had a more detrimental effect on participants' performance than when a visual mask was used. This result might suggest that distractors presented within the same sensory modality as the change are more effective in drawing spatial attention to themselves than are distractors presented in another sensory modality. It should be noted that the results of Experiment 2 might also be taken to suggest that certain of the processes underlying change detection in humans are modality-specific (accounting for the fact that participants' performance was more deleteriously affected by the presentation of a tactile mask than by the presentation of a visual mask) whereas others are multisensory (accounting for the influence of a visual mask on tactile change detection).

In Experiment 2, the auditory mask (presented by means of loudspeakers located in front of the participants) did not impair participants' performance as compared with the empty interval condition. Experiment 3 was therefore conducted in order to investigate whether the influence of the auditory mask on tactile change detection performance might be unaffected by the degree of spatial congruency between the auditory mask and changes in the tactile displays. The results revealed that the auditory mask (displayed by means of loudspeaker cones located below the participants' fingers) had the same effect on participants' performance no matter whether or not it was presented from the same side as the change. This result suggests that, in the case of tactile change detection, performance might be independent of any spatial congruency between the tactile target and the auditory mask. In line with this hypothesis, it should be mentioned that previous studies have shown that tactile change detection performance is impaired by visual masks and this occurs both when the participants viewed the visual distractors by directly looking at their body and via a mirror reflection (Gallace et al., 2006a).

The existence of dominance among sensory modalities might explain the lack of effect of the auditory mask on tactile change detection. It has been suggested that, for a specific task, the information from one sensory modality will be dominant over the information from another if it has a lower level of variance (see Ernst and Banks, 2002; see also Bresciani and Ernst, 2007, for similar claims regarding sensory dominance as a function of the reliability of the tactile and auditory signals). With regard to change detection, the results of the present study show that visual distractors can impair tactile change detection. By contrast, previous research by Auvray et al. (2007) has shown that tactile distractors fail to affect visual change detection. Similarly, it could be the case that, with regard to the detection of positional changes, touch dominates audition with, as a result, auditory distractors failing to impair tactile change detection.

In addition, the asymmetries between the auditory, tactile, and visual stimuli in terms of spatial interactions can provide an explanation for the pattern of results reported in the present study: Numerous studies on the interactions between vision, touch, and proprioception have revealed the existence of multisensory/amodal spatial representations that code external events with respect to observers' bodies (see Spence and Driver, 2004, for a review). On the other hand, spatial modulations do not always affect audio-tactile interactions (see Kitagawa and Spence, 2006, for a review). One of the reasons put forward by Kitagawa and Spence (2006) for this absence of audio-tactile spatial interactions is that most of the studies were performed with the auditory stimuli presented in front of the observers. However, recent research has shown that audio-tactile interactions are more prevalent for stimuli that are presented in close proximity of the observers' heads than for stimuli presented in front of them, such as near the hands (e.g., Zampini et al., 2005; see also Tajadura-Jiménez et al., submitted for publication). Thus, the absence of an effect of the auditory distractors on tactile change detection observed in our study can perhaps be accounted for by the fact that the tactile and auditory stimuli were presented from the region of space around the participants' hands. In order to further highlight the interactions between audition, vision, and touch, it would be interesting in future research to investigate the influence of visual and tactile distractors on the detection of changes between two auditory displays (cf. Chan and Spence, submitted for publication).

In summary, the three experiments reported here further highlight the similarities and differences between the change blindness effects reported previously within vision, audition, and touch. The larger effect of the tactile mask (versus visual mask) on tactile change detection performance and the absence of any effect of the auditory mask suggest that certain of the processes underlying change blindness are modality-specific in nature. In addition, the possibility of eliciting tactile change blindness with visual distractors suggests that some similar mechanisms may contribute to the change blindness effects observed within the visual, tactile and auditory modalities (see Downar et al., 2000).

4. Experimental procedure

4.1. *Participants*

Twelve participants (7 females and 5 males) took part in Experiment 1 (mean age of 21 years, range of 19–26 years). Twelve new participants (8 females and 4 males) took part in Experiment 2 (mean age of 20 years, range of 18–24 years), and a further 14 new participants (6 females and 8 males) took part in Experiment 3 (mean age of 25 years, range of 20–28 years). All of the participants had normal or corrected to normal vision and reported normal tactile and auditory perception. They received a five pound (UK Sterling) gift voucher in return for their participation. The experiment took approximately 45 min to complete and was performed in accordance with the ethical standards laid down in the 1991 Declaration of Helsinki.

4.2. *Apparatus and materials*

The participants were presented with tactile stimulus patterns delivered by means of eight resonant-type tactors (Part No: VBW32, Audiological Engineering Corp., Somerville, MA, USA) with 1.6 × 2.4 cm vibrating surfaces. The vibrators were driven by means of a custom-built 9-channel amplifier circuit (Haptic Interface Research Laboratory, Purdue University, Indiana, USA) that drove each tactor independently at 290 Hz (close to its resonant frequency). One tactor was placed on each finger of both of the participants' hands (see Fig. 3).

The intensity of each tactor was adjusted individually at the beginning of each experimental session in order that each vibrotactile stimulus could be perceived clearly, and that all of the vibrotactile stimuli were perceived to be of a similar intensity. The amplification levels of the tactors were kept at their individually-chosen levels throughout the experiment. Stimulus presentation was controlled through the serial port of

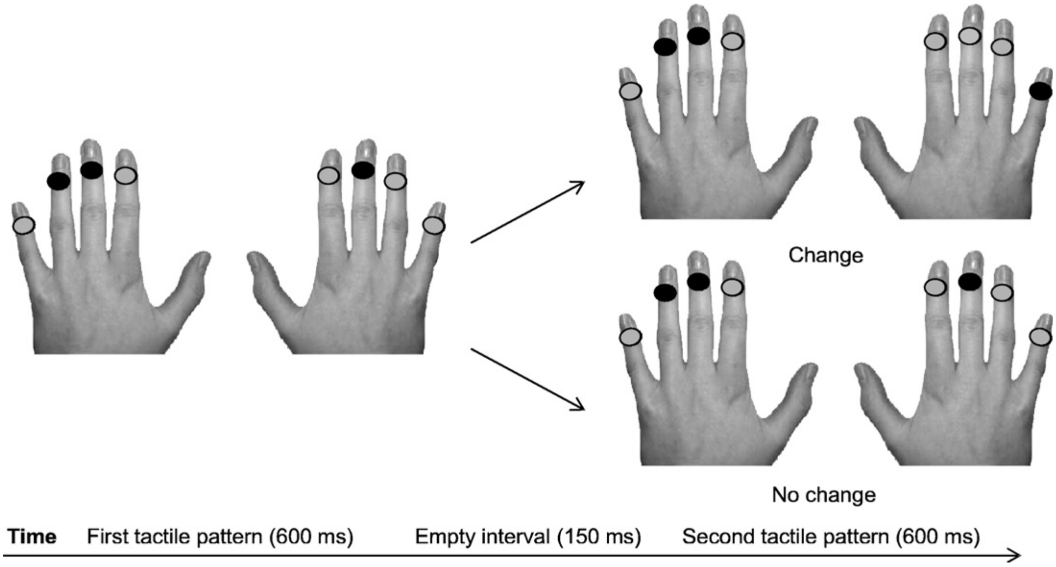

Fig. 3 – Schematic figure highlighting the change and no change conditions during the empty interval block of Experiments 1 and 2. The black circles represent the activated tactors and the grey circles represent the non-activated tactors.

a laptop computer running custom software written in Matlab 6.0. White noise was presented over closed-ear headphones at 70 dB(A) to mask any sound made by the activation of the tactors.

4.3. *Procedure of experiment 1*

The participants completed three experimental conditions in three separate sessions, respectively. In one condition, the two to-be-compared tactile patterns were presented consecutively for 600 ms each. In the second condition, the two patterns were separated by a 150 ms empty interstimulus interval. In the third condition, the two patterns were separated by a 50 ms empty interstimulus interval, followed by a 50 ms mask, and then a second 50 ms empty interstimulus interval. The mask consisted of the activation of one of the tactors. The order of presentation of these three experimental conditions was randomly varied across participants.

In each block of trials, the stimulus patterns consisted of the activation of 3 tactile stimuli. In half of the trials, 2 stimuli were presented on the left hand and one stimulus on the right hand, and the reverse in the other half of the trials. In addition, in half of the trials, the two patterns of stimuli were presented from the same locations ("no change condition") and in the other half of the trials, one of the stimuli composing the first pattern moved to a different position within the same hand when the second pattern was presented ("change condition") (see Fig. 3). Finally, in the tactile mask block, the mask was displayed on the participant's right hand in half of the trials and on the participant's left hand in the other half of the trials. Within a given hand, the positions of the tactors constituting the display and the mask were randomized across the trials.

The participants sat on a chair, in an experimental chamber, for the duration of the experiment. Their hands rested on a table in front of them and their right foot was placed on two footpedals. The participants were instructed to raise their heel as soon as they detected that a change in position had occurred between the two sequentially-presented stimulus patterns and to raise their toes if there was no change in the displays (half of the participants performed the experiment with the reversed footpedal arrangement: raising their toes if they decided that a change had occurred and their heel otherwise).

Before completing the experimental conditions, the participants were given 10 practice trials in each of the 3 different conditions. Next, they completed 128 test trials per experimental condition with each participant completing 384 trials in total. The participants were able to make their unspeeded discrimination response at any time up to 4000 ms after the onset of the second pattern (at which point the trial was terminated). No feedback was given regarding the correctness of the participants' responses.

4.4. *Procedure of experiment 2*

The materials and procedure were the same as those reported for Experiment 1 with the following exceptions: green LEDs were now mounted at the same position as the tactors. The participants were able to see the LEDs by looking directly at their fingertips. Two loudspeakers were placed on the table upon which the participants rested their hands, 25 cm to the left and to the right of their body midline. The participants completed four separate blocks of 128 trials with each participant completing 512 trials in total. The order of presentation of the four blocks was randomly varied across the participants. In one experimental condition, the two to-be-compared tactile patterns were separated by a 150 ms empty interstimulus interval. In the other three conditions, the two patterns of tactile stimulation were separated by a 50 ms empty interstimulus interval, followed by a 50 ms mask, and then by a second 50 ms empty interstimulus interval. In one of these 3 conditions the mask consisted of the activation of one of the tactors, in the second condition the mask consisted of the activation of one of the LEDs, and in the third condition the mask consisted of the presentation of a 100 dB(A) white noise sound from one of the two loudspeaker cones. In this experiment, the participants did not wear headphones in order not to impair their ability to hear the auditory mask.

4.5. *Procedure of experiment 3*

The materials and procedure were the same as those reported for Experiment 2 with the following exceptions: The participants rested each hand over a loudspeaker cone, one placed 25 cm to the left and to the right of their body midline on the table in front of the participant. The participants completed 128 trials in which the two to-be-compared displays consisted of the sequential presentation of three tactile stimuli. The two displays were presented for 600 ms each separated by an “auditory mask” consisting of a 50 ms empty interstimulus interval, followed by a white noise burst presented at 100 dB(A) for 50 ms and then by a second 50 ms empty interstimulus interval.

REFERENCES

Auvray, M., O’Regan, J.K., 2003. L’influence des facteurs sémantiques sur la cécité aux changements progressifs dans les scènes visuelles (The influence of semantic factors on blindness to progressive changes in visual scenes). Année Psychol. 103, 9–32.

Auvray, M., Gallace, A., Tan, H.Z., Spence, C., 2007. Crossmodal change blindness between vision and touch. Acta Psychol. 126, 79–97.

Beck, D.M., Muggleton, N., Walsh, V., Lavie, N., 2006. Right parietal cortex plays a critical role in change blindness. Cereb. Cortex 16, 712–717.

Bresciani, J.P., Ernst, M.O., 2007. Signal reliability modulates auditory-tactile integration for event counting. NeuroReport 18, 1157–1161.

Cartwright-Finch, U., Lavie, N., 2007. The role of perceptual load in inattentional blindness. Cognition 102, 321–340.

Chan, J.S., & Spence, C., (submitted for publication). Change deafness: An auditory analogue of visual change blindness?

Demany, L., Trost, W., Serman, M., Semal, C., 2008. Auditory change detection: simple sounds are not memorized better than complex sounds. Psychol. Sci. 19, 85–91.

Downar, J., Crawley, A.P., Mikulis, D.J., Davis, K.D., 2000. A multimodal cortical network for the detection of changes in the sensory environment. Nat. Neurosci. 3, 277–283.

Eramudugolla, R., Irvine, D.R.F., McAnally, K.I., Martin, R.L., Mattingley, J.B., 2005. Directed attention eliminates ‘change deafness’ in complex auditory scenes. Curr. Biol. 15, 1108–1113.

Ernst, M.O., Banks, M.S., 2002. Humans integrate visual and haptic information in a statistically optimal fashion. Nature 415, 429–433.

Ernst, M.O., Bülthoff, H.H., 2004. Merging the senses into a robust percept. Trends Cogn. Sci. 8, 162–169.

Gallace, A., Spence, C., 2008. The cognitive and neural correlates of “tactile consciousness”: A multisensory perspective. Consciousness & Cognition 17, 370–407.

Gallace, A., & Spence, C., (submitted for publication). The cognitive neuroscience of tactile memory. Psychological Bulletin.

Gallace, A., Auvray, M., Tan, H.Z., Spence, C., 2006a. When visual transients impair tactile change detection: A novel case of crossmodal change blindness? Neurosci. Lett. 398, 280–285.

Gallace, A., Tan, H.Z., Spence, C., 2006b. The failure to detect tactile change: a tactile analog of visual change blindness. Psychon. Bull. Rev. 13, 300–303.

Gallace, A., Tan, H.Z., Spence, C., 2007. Do “mudsplashes” induce tactile change blindness? Percept. Psychophys. 69, 477–486.

Gallace, A., Tan, H.Z., & Spence, C., in press. Can tactile stimuli be subitized? An unresolved controversy within the literature on numerosity judgments. Perception.

Ghazanfar, A.A., Schroeder, C.E., 2006. Is neocortex essentially multisensory? Trends Cogn. Sci. 10, 278–285.

Guest, S., Catmur, C., Lloyd, D., Spence, C., 2002. Audiotactile interactions in roughness perception. Exp. Brain Res. 146, 161–171.

Ho, C., Santangelo, V., & Spence, C., (submitted for publication). Multisensory warning signals: When spatial correspondence matters. J. Exp. Psychol. Applied.

Irwin, D.E., 1991. Information integration across saccadic eye movements. Cogn. Psychol. 23, 420–456.

Jousmäki, V., Hari, R., 1998. Parchment-skin illusion: sound-biased touch. Curr. Biol. 8, R190.

Kitagawa, N., Spence, C., 2006. Audiotactile multisensory interactions in human information processing. Japanese Psychol. Res. 3, 158–173.

Koivisto, M., Revonsuo, A., 2006. An ERP study of change detection, change blindness, and visual awareness. Psychophysiology 40, 423–429.

Lavie, N., 2006. The role of perceptual load in visual awareness. Brain Res. 1080, 91–100.

Levin, D.T., Simons, D.J., 1997. Failure to detect changes to attended objects in motion pictures. Psychon. Bull. Rev. 4, 501–506.

Lloyd, D.M., Merat, N., McGlone, F., Spence, C., 2003. Crossmodal links between audition and touch in covert endogenous spatial attention. Percept. Psychophys. 65, 901–924.

Macmillan, N.A., Creelman, C.D., 2004. Detection theory: A user’s guide, 2nd. Lawrence Erlbaum Associates, New York.

Menning, H., Ackermann, H., Hertrich, I., Mathiak, K., 2005. Spatial auditory attention is modulated by tactile priming. Exp. Brain Res. 164, 41–47.

Murray, M.M., Molholm, S., Michel, C.M., Heslenfeld, D.J., Ritter, W., Javitt, D.C., Schroeder, C.E., Foxe, J.J., 2005. Grabbing your ear: rapid auditory-somatosensory multisensory interactions in low-level sensory cortices are not constrained by stimulus alignment. Cereb. Cortex 15, 963–974.

Nakamura, A., Yamada, T., Goto, A., Kato, T., Ito, K., Abe, Y., et al., 1998. Somatosensory homunculus as drawn by MEG. Neuroimage 74, 377–386.

Narici, L., Modena, I., Opsomer, R.J., Pizzella, V., Romani, G.L., Torrioli, G., et al., 1991. Neuromagnetic somatosensory homunculus: a non-invasive approach in humans. Neurosci. Lett. 121, 51–54.

O’Regan, J.K., Rensink, R.A., Clark, J.J., 1999. Change-blindness as a result of ‘mudsplashes’. Nature 398, 34.

O’Regan, J.K., Deubel, H., Clark, J.J., Rensink, R.A., 2000. Picture changes during blinks: looking without seeing and seeing without looking. Vis. Cogn. 7, 191–211.

Pisella, L., Berberovic, N., Mattingley, J.B., 2004. Impaired working memory for location but not for colour or shape in visual neglect: a comparison of parietal and non-parietal lesions. Cortex 40, 379–390.

Rensink, R.A., O’Regan, J.K., Clark, J.J., 1997. To see or not to see: the need for attention to perceive changes in scenes. Psychol. Sci. 8, 368–373.

Simons, D.J., 1996. In sight, out of mind: when object representations fail. Psychol. Sci. 7, 301–305.

Simons, D.J., Franconeri, S.L., Reimer, R.L., 2000. Change blindness in the absence of visual disruption. Perception 29, 1143–1154.

Simons, D.J., Rensink, R.A., 2005. Change blindness: past, present, and future. Trends Cogn. Sci. 9, 16–20.

Spence, C., Driver, J. (Eds.), 2004. Crossmodal space and crossmodal attention. Oxford University Press, Oxford, UK.

Spence, C., McDonald, J., Driver, J., 2004. Exogenous spatial-cueing studies of human cross-modal attention and multisensory integration. In: Spence, C., Driver, J. (Eds.), Crossmodal space and crossmodal attention. Oxford University Press, Oxford, pp. 277–320.

Tajadura-Jiménez, A., Kitagawa, N., Väljamäe, A., Zampini, M., Murray, M.M., & Spence, C., (submitted for publication). Auditory-tactile multisensory interactions are spatially modulated by stimulated body surface & acoustic spectra.

Vitevitch, M.S., 2003. Change deafness: the inability to detect changes between two voices. J. Exp. Psychol. Hum. Percept. Perform. 29, 333–342.

Zampini, M., Brown, T., Shore, D.I., Maravita, A., Röder, B., Spence, C., 2005. Audiotactile temporal order judgments. Acta Psychol. 118, 277–291.

Zampini, M., Torresan, D., Spence, C., Murray, M., 2007. Auditory-somatosensory interactions in front and rear space. Neuropsychologica 45, 1869–1877.