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Crossmodal change blindness between vision and touch

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Abstract

Change blindness is the name given to people's inability to detect changes introduced between two consecutively-presented scenes when they are separated by a distractor that masks the transients that are typically associated with change. Change blindness has been reported within vision, audition, and touch, but has never before been investigated when successive patterns are presented to different sensory modalities. In the study reported here, we investigated change detection performance when the two to-be-compared stimulus patterns were presented in the same sensory modality (i.e., both visual or both tactile) and when one stimulus pattern was tactile while the other was presented visually or vice versa. The two to-be-compared patterns were presented consecutively, separated by an empty interval, or else separated by a masked interval. In the latter case, the masked interval could either be tactile or visual. The first experiment investigated visual–tactile and tactile–visual change detection performance. The results showed that in the absence of masking, participants detected changes in position accurately, despite the fact that the two to-be-compared displays were presented in different sensory modalities. Furthermore, when a mask was presented between the two to-be-compared displays, crossmodal change blindness was elicited no matter whether the mask was visual or tactile. The results of two further experiments showed that performance was better overall in the unimodal (visual or tactile) conditions than in the crossmodal conditions. These results suggest that certain of the processes underlying change blindness are

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multisensory in nature. We discuss these findings in relation to recent claims regarding the crossmodal nature of spatial attention.

Keywords: Spatial perception; Change blindness; Attention; Multisensory perception; Sensory modality

1. Introduction

The large body of empirical research on the phenomenon of change blindness in vision demonstrates that observers often experience difficulties in detecting changes taking place between successive views of a visual scene when some form of disruption (or transient) occurs between the two presentations of the scene. Change blindness has been observed when changes occur during saccades (Henderson, 1997; Irwin, 1991), eye blinks (O'Regan, Deubel, Clark, & Rensink, 2000), when a blank screen, or "flicker", is inserted between the original and modified images (Pashler, 1988; Rensink, O'Regan, & Clark, 1997; Simons, 1996), and when small black-and-white "mudsplashes" are superimposed over parts of the image during the change (even though the mudsplashes themselves do not cover the change; O'Regan, Rensink, & Clark, 1999). Change blindness can also be elicited when changes occur very slowly (Auvray & O'Regan, 2003; Simons, Franconeri, & Reimer, 2000), when scene cuts occur in film sequences (Hochberg, 1986; Levin & Simons, 1997), during real-life change (Simons & Levin, 1998), and by constant and smooth oscillatory motion of the whole image (even in the absence of any other form of masking during the change; Schofield, Bishop, & Allan, 2006).

Explanations of the phenomenon of change blindness in vision are usually based on the notion that the visual system is particularly sensitive to changes in colour or luminance in the visual field (see Simons & Rensink, 2005). Under normal viewing conditions, these changes create a transient signal in the visual field that is detected by low-level perceptual mechanisms, and hence attention is thought to be exogenously attracted to the location of the change. Change blindness paradigms are therefore considered to work because they utilize experimental protocols that successfully mask the local transients that would normally be associated with change. Given that attention is no longer attracted to the location of any 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). The particular elements in a given scene on which we happen to focus our attention reflect both physical factors, such as the salience (size, intensity, etc.) of the stimuli, as well as semantic factors, such as their interest (central vs. marginal) or scene consistency (e.g., Auvray & O'Regan, 2003; Gibson & Crooks, 1938; Rensink et al., 1997).

Change blindness is not, however, restricted to the visual modality. The inability of people to detect a change occurring at the same time as some form of disruption has also been reported within the auditory modality, where the phenomenon has been labelled 'change deafness'. For example, when participants in a study by Vitevitch (2003) had to repeat a stream of words in a shadowing task, they failed to detect the change in the identity of the talker. Change deafness can also be elicited when a white noise auditory mask is presented at the same time as a change in a talker's identity (Chan & Spence, submitted for publication; see also Eramudugolla, Irvine, McAnally, Martin, & Mattingley, 2005). Change blindness has recently been reported within the tactile modality as well (Gallace, Tan, & Spence, 2006a, in press). The results of these various studies of change detection in different sensory modalities support the view that our perception of sensory events is critically dependent upon attention, regardless of the modality of occurrence of those events.

The following question therefore arises: Is change blindness related to a modal or to a multisensory/amodal underlying mechanism? Furthermore, are attentional processes and spatial encoding unimodal or multisensory in nature? The experimental studies described thus far demonstrate that distractors presented within the same sensory modality as the change can elicit change blindness. Recent research by Gallace, Auvray, Tan, and Spence (2006) has shown that observers often fail to detect the presence of positional changes between two sequentially-presented vibrotactile patterns on the body surface not only when vibrotactile distractors are used to mask the change, but also when visual distractors are used instead. These results therefore suggest that the transients used to elicit change blindness do not necessarily have to occur in the same sensory modality as the change; presumably because their primary role is to attract attention away from the change, and crossmodal cues can be just as effective as intramodal cues in this regard (see Spence, McDonald, & Driver, 2004).

To date, however, no previous behavioral studies have investigated the possibility that change blindness might occur crossmodally when the two to-be-compared patterns of stimulation are actually presented in different sensory modalities. Therefore, in the three experiments reported here, we investigated change detection performance for pairs of stimulus patterns presented in either the same (both visual or both tactile) or different (one tactile and the other visual) sensory modalities. At least two possible (and somewhat contradictory) hypotheses can be put forward regarding the expected results of this study.

On the one hand, if the phenomenon of change blindness relies primarily on the masking of the transient signals that normally accompany change (e.g., Simons & Rensink, 2005), one might predict that change detection performance should be much worse under conditions of crossmodal stimulation than under unimodal conditions (at least when the transient signals that accompany change are not prevented from playing their 'attention-grabbing' role). This is primarily because the motion transients associated with a change in position are stronger when the two to-be-compared stimulus patterns are presented within the same sensory modality than when they are presented in different modalities (e.g., Harrar, Winter, & Harris, 2005; Sanabria, Soto-Faraco, & Spence, 2005). However, this prediction also follows on from the fact that the crossmodal presentation of the two to-be-compared stimulus patterns will necessarily generate many transients due to the change in the sensory modality of the stimuli presented at each of the locations making up each of the patterns. Thus, it would be possible that these numerous modality-change transients could mask any motion transients associated with the change in position of one of the stimuli itself.

On the other hand, given the existence of extensive crossmodal links in spatial attention (e.g., see Spence et al., 2004, for a review), one might predict first that the processes underlying the encoding of spatial positions should also be multisensory in nature. Thus, change detection should be possible across different sensory modalities. Second, according to this view, one might also predict that it should be possible to elicit change blindness by means of masking stimuli in the same way under both unimodal tactile as well as crossmodal tactile–visual conditions of stimulus presentation.

2. Experiment 1

In the first experiment, we investigated change detection performance when the first stimulus pattern presented to participants was tactile and the second visual, and conversely, when the first stimulus pattern was visual and the second tactile. The two to-be-compared displays consisted of simple patterns of stimulation that could either be presented consecutively, separated by an empty interval, or else separated by a masked interval.

3. Methods

3.1. Participants

Sixteen participants (9 females and 7 males) took part in this experiment. Their ages ranged from 19 to 33 years (mean: 25.5 ± S.D. of 4.7 years). All of the participants had normal or corrected to normal vision and reported normal tactile perception. They received a five pound (UK Sterling) gift voucher in return for their participation. The experiment took approximately 45 min to complete. The experiment was performed in accordance with the ethical standards laid down in the 1991 Declaration of Helsinki.

3.2. Apparatus and materials

The vibrotactile stimuli were presented by means of six resonant-type tactors (Part No: VBW32, Audiological Engineering Corp., Somerville, MA, USA) with 1.6 × 2.4 cm vibrating surfaces. The tactors were placed on the participants' body over the top of any clothing that they happened to be wearing by means of Velcro strip belts. 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). The intensity of each tactor was adjusted individually at the start of each participant's experimental session, in order to ensure 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. The visual stimuli consisted of green LEDs positioned in the same positions as the tactors but mounted on the other side of the belts (see Fig. 1 for the position of the tactors and LEDs on participants' bodies). The participants viewed the LEDs by looking directly at their own body.[1] Stimulus presentation was controlled through the serial port of 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 vibrotactile stimulators.

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[1] It should be noted that in contrast to previous studies using similar materials (Gallace, Auvray, et al., 2006), the participants in the present study actually looked directly at the lights displayed on their body, rather than looking at a mirror reflection of the lights on their body. We used direct viewing here in order to prevent any left–right confusion that viewing one's mirror reflection might have introduced (e.g., Gregory, 1997; see also Snyder, Grieve, Brotchie, & Andersen, 1998).

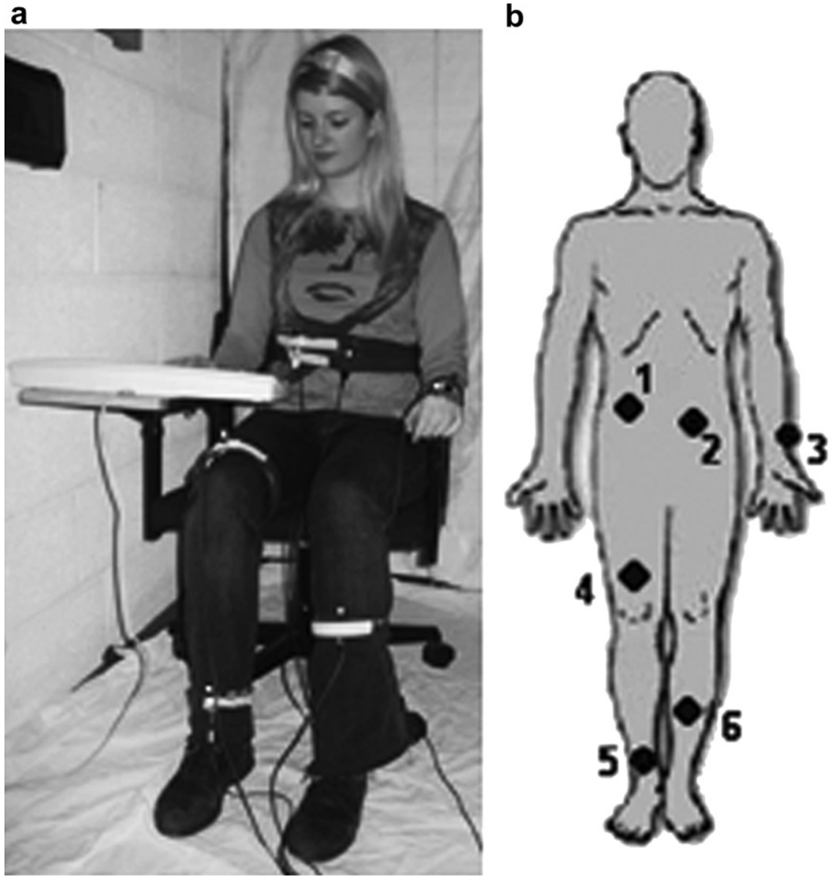

Fig. 1. (a) Participant in the seated posture adopted during the experiment with tactors and vibrators attached to their body. (b) Schematic figure highlighting the positions on the body surface where the tactors and LEDs were placed: (1) on the waistline, to the right of the body midline; (2) to the left of the body midline; (3) on the left wrist; (4) just above the right knee; (5) just above the right ankle and (6) midway between the ankle and the knee on the left leg.

3.3. Procedure

The experiment consisted of two experimental conditions each presented in a separate session. In one condition, the first stimulus consisted of a vibratory pattern and the second consisted of a visual pattern, both of which were presented for 600 ms. In the other experimental condition, the stimulus patterns were the same but their order of presentation was reversed. The order of presentation of these two experimental conditions was counterbalanced across participants.

The no interval, empty interval, and masked interval conditions were each presented in a separate block of experimental trials. In the first block, the two patterns of stimulation were presented sequentially (i.e., without any gap between them). In the second block, the two patterns were separated by a 250 ms empty interstimulus interval. In the third block, the two patterns were separated by a 50 ms empty interstimulus interval, followed by a

150 ms mask, and then by a second 50 ms empty interstimulus interval (i.e., the total duration of the interval was again 250 ms). In half of the trials, the mask consisted of the illumination of all 6 LEDs on the participants' body, while on the other half of the trials, the mask consisted of the activation of all six tactors instead. The order of presentation of these three block types was randomly varied across participants.

In each block of trials, the patterns of stimulation consisted of either 2 or 3 tactors or LEDs presented equally frequently from each of the six possible bodily locations. In half of the trials, the two patterns of stimulation were presented from the same body locations ("no change condition"). In the other half of the trials, one of the stimuli composing the first pattern moved to a different position in the second pattern ("change condition").

The experiment was conducted in an experimental chamber under conditions of low ambient illumination in order to ensure that the participants could clearly see the visual stimuli attached to their body when illuminated. The participants sat on a chair for the duration of the experiment. The experimenter made sure that they could clearly see all of the LEDs. The participants were instructed to press one of the two response keys on a computer keyboard as soon as they decided whether or not a change in position had occurred between the two patterns of stimulation. The participants could make their unspeeded discrimination response at any time up to 4000 ms after the onset of the second pattern. The participants were given no feedback regarding the correctness of their responses. The participants were given 10 practice trials before completing 64 experimental trials in each block. Each participant completed a total of 384 trials.

4. Results

Trials in which participants failed to make a response before the trial was terminated (less than 8% 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, experimental session, and block type using signal detection theory (e.g., Macmillan & Creelman, 2004; see Fig. 2).

Initial ANOVAs were conducted on the d' and β data with three factors: stimulation (tactile–visual vs. visual–tactile), block type (no interval, empty interval, and masked inter-

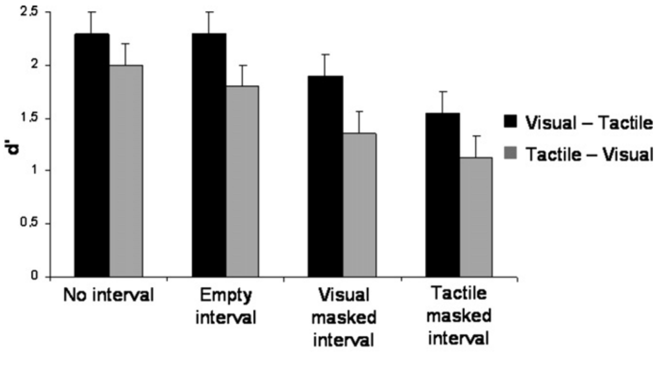

Fig. 2. Participants' mean performance (d') for the two conditions of stimulus presentation: visual–tactile (in black) and tactile–visual (in gray); and for the four interval conditions: no interval, empty interval, visual masked interval, and tactile masked interval (Experiment 1). Error bars represent the standard errors of the means.

val), and the number of stimuli composing the display (2 vs. 3). Analysis of the d' data revealed a significant main effect of stimulation [$F(1,15) = 23.51$, $p < .001$], a significant main effect of block type [$F(2,30) = 36.22$, $p < .0001$], and a significant main effect of the number of stimuli presented [$F(1,15) = 40.71$, $p < .0001$]. The analysis did not show any interactions between stimulation, block type, and the number of stimuli factors (all Fs < 1). A Duncan post-hoc test on the block type factor revealed that participants' performance was significantly worse in the masked interval block (mean: 1.5 ± S.E. of 0.1) than in the other two block types: no interval (mean: 2.2 ± 0.2) and empty interval blocks (mean: 2.1 ± 0.1) (both ps < .005), but that there was no significant difference between these latter two conditions. With regard to the stimulation factor, participants responded more accurately in the visual–tactile condition (mean: 2.1 ± 0.1) than in the tactile–visual condition (mean: 1.7 ± 0.1). It should be noted that the raw error data showed the same trend as did the analysis of the d' data. The percentage of correct change detection responses for the no interval, empty interval, and masked interval blocks were 82.4%, 79.7%, and 71.6% in the tactile–visual condition, and 84.8%, 84.1%, and 78.5% in the visual–tactile condition, respectively. With regard to the number of stimuli factor, the participants responded more accurately when the display patterns were composed of two stimuli (mean: 2.2 ± 0.1) than when they were composed of three stimuli (mean: 1.5 ± 0.1). This result is similar to those obtained in previous studies of unimodal tactile and visual change detection (Gallace et al., 2006a; Wright, Green, & Baker, 2000).

The analysis of the response bias data β did not reveal any main effect of block type [$F(2,30) = 1.08$, n.s.], nor of the number of stimuli [$F(1,15) < 1$, n.s.], nor any interactions between the stimulation, block type, and number of stimuli factors (all Fs < 1). However, the analysis did show a significant main effect of stimulation [$F(1,15) = 10.03$, $p < .01$]. β values were lower in the tactile–visual condition (mean: 1.24 ± 0.08) than in the visual–tactile condition (mean: 1.56 ± 0.12). However, the distribution of participants' responses did not allow for any obvious explanation of these results. An additional ANOVA was performed on the raw error data with three factors: stimulation, block type, and presence versus absence of change between the two patterns of stimuli composing the displays. The analysis revealed a significant main effect of the presence versus absence of change [$F(1,15) = 5.39$, $p < .05$], but did not show any interactions with either stimulation or block type (both Fs < 1). Thus, in both conditions of stimulation, the participants made more errors when there was a change (23.4% failure to detect a change) than when there was no change (16.1% false alarm rate). This result is similar to the results obtained in the previous studies of unimodal change blindness (e.g., Simons, 2000) 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.

An ANOVA performed on the d' and β data from the masked interval blocks as a function of the masking modality (visual vs. tactile) and stimulation (tactile–visual vs. visual–tactile) did not show any effect of masking modality on d', nor interaction with stimulation (Fs < 1). Likewise, the analysis of the response bias data did not reveal any effect of masking modality, nor interaction with the stimulation factor (both Fs < 1).

An ANOVA performed on all the RT data (including both the correct and incorrect responses) with the factors of stimulation and block type did not show any effect of stimulation [$F(1,15) < 1$, n.s.], nor any interaction between stimulation and block type [$F(2,30) < 1$, n.s.]. However, the analysis did reveal an effect of block type [$F(2,30) = 15.62$, $p < .001$]. A Duncan post-hoc test revealed that participants responded significantly faster in the masked interval block (1542 ± S.E. of 62 ms) than in the other two block types: no interval (1352 ± 55 ms) and empty interval blocks (1369 ± 62 ms) (both *p*s < .05), but that there was no significant difference between these latter two conditions.

5. Discussion

The first important result to emerge from the analysis of Experiment 1 was that in the absence of any masking being presented in the interval between the two patterns, participants were able to detect the presence of positional changes between the two displays, even though they were presented in different sensory modalities. The participants' perceptual sensitivity for the no interval and empty interval blocks were 2.3 and 2.3 in the visual–tactile condition, and 2.0 and 1.8 in the tactile–visual condition, respectively. These values were higher than 1.0, which is typically used as the detection threshold criterion. Thus, the participants were able to detect crossmodal changes despite the presence of transients generated by the change in the sensory modality of the stimuli presented at each of the locations making up each of the patterns. However, change detection performance was significantly better overall in the visual–tactile condition than in the tactile–visual condition. It thus seems that the transients generated by the change in sensory modality are more effective in disrupting the encoding of spatial positions when the first pattern is tactile than when it is presented visually.

The second main result to emerge from the analysis of Experiment 1 was that participants' performance in detecting positional changes was impaired by the presence of a masked interval as compared to both the empty interval and no interval conditions. This result suggests that the transients generated by (or associated with) the presentation of the mask impaired participants' performance more than the transients associated with the change of modality in the presentation of the two target displays. Recent studies have shown that the motion transients associated with a change in the position of a stimulus are stronger when the two to-be-compared stimuli are presented within the same sensory modality than when they are presented in different sensory modalities (e.g., Harrar et al., 2005; Sanabria et al., 2005). The existence of such crossmodal apparent motion (albeit much weaker than unimodal apparent motion) could explain the fact that crossmodal change detection is impaired when a masked interval is introduced between the two to-be-compared patterns.

Interestingly, in our study, visual and tactile masks were found to impair participants' performance just as effectively in both the visual–tactile and tactile–visual conditions. This result suggests that certain of the processes underlying change detection may be multisensory in nature. If this were not to have been the case, then we should have found an asymmetry in participants' performance as a function of the modality of the mask. That is, the modality of the mask should have interfered with performance more when it matched the modality of presentation of the first pattern, and hence masked it (cf. Gescheider & Niblette, 1967; Soto-Faraco et al., 2002).

In summary, the results of Experiment 1 suggest on the one hand that the visual and haptic systems have different encoding/memory limitations (i.e., we found an asymmetry between the visual–tactile and tactile–visual conditions). On the other hand, the fact that participants were able to perform the crossmodal detection task in the absence of any masking and the similar effect of visual and tactile masks on performance suggest that certain of the processes underlying the detection of positional changes are multisensory in nature. Thus, in order to investigate the extent to which the mechanisms underlying change detection are multisensory, we conducted a second experiment in which we compared the ability of participants to detect positional changes when both of the stimulus displays were tactile and when the first was tactile and the second was presented visually.

6. Experiment 2

6.1. Methods

The materials and procedure were similar to those reported for Experiment 1 with the following difference: in one experimental condition, the two patterns of stimulation consisted of vibrotactile displays presented for 600 ms each. In the other condition, the first pattern was vibrotactile while the second was presented visually, just as in Experiment 1.

6.2. Participants

Eighteen participants (9 females and 9 males) took part in this experiment. Their ages ranged from 20 to 34 years (mean: 25.6 ± S.D. of 4.3 years). All of the participants had normal or corrected to normal vision and reported normal tactile perception. They received a five pound (UK Sterling) gift voucher in return for their participation. The experiment took approximately 45 min to complete.

7. Results and discussion

Trials in which participants failed to make a response before the trial was terminated (<8% of trials overall) were not included in the data analyses. ANOVAs were conducted on the d' and β data with three factors: stimulation (unimodal tactile stimulation vs. crossmodal tactile–visual stimulation), block type (no interval, empty interval, and masked interval), and number of stimuli composing the display (2 vs. 3). Analysis of the d' data revealed a significant main effect of stimulation [$F(1,17) = 72.23$, $p < .0001$], a significant effect of block type [$F(2,34) = 43.8$, $p < .0001$], and a significant effect of the number of stimuli [$F(1,17) = 42.90$, $p < .0001$]. There was no interaction between either stimulation and block type, block type and the number of stimuli (both Fs < 1), or between stimulation and number of stimuli [$F(1,17) = 1.48$, $p = .24$].

A Duncan post-hoc test on the block type factor revealed that participants' performance was significantly worse in the masked interval block (mean: 1.5 ± S.E. of 0.1) than in the other two block types: no interval (mean: 2.4 ± 0.2) and empty interval blocks (mean: 2.2 ± 0.1) (both ps < .005), but that there was no significant difference between the latter two conditions. With regard to the stimulation factor, participants responded more accurately in the tactile–tactile condition (mean: 2.4 ± 0.1) than in the tactile–visual condition (mean: 1.7 ± 0.1) (see Fig. 3). With regard to the number of stimuli factor, the participants responded more accurately when the display patterns were composed of two stimuli (2.3 ± 0.1) than when they were composed of three stimuli (1.8 ± 0.1; cf. Gallace et al., 2006a). The analysis of the response bias data (β) revealed a significant interaction between the number of stimuli presented and the stimulation factor [$F(1,17) = 7.12$, $p < .05$]. A Duncan post-hoc test showed that in the tactile–visual condition β was larger for three stimuli than for two stimuli ($p < .05$), whereas no such difference was reported in the tactile–tactile

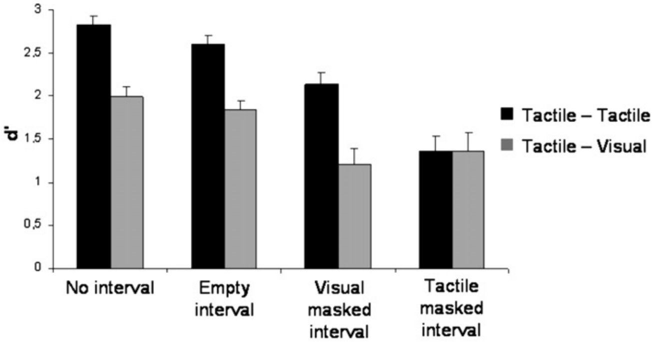

Fig. 3. Participants' mean performance (*d*′) for the two conditions of stimulus presentation: tactile–tactile (in black) and tactile–visual (in gray); and for the four interval conditions: no interval, empty interval, visual masked interval, and tactile masked interval (Experiment 2). Error bars represent the standard errors of the means.

condition (although note that the numerical trend was in the same direction). The analysis did not reveal any other significant terms (all *F*s < 1).

An ANOVA performed on all of the raw error data revealed a significant main effect of the presence versus absence of change [$F(1,17) = 5.94$, $p < .05$], but no interaction with block type, nor with stimulation (both *F*s < 1). Participants made more errors on trials where there was a change (19.0% failure to detect a change) than on trials when there was no change (13.3% false alarm rate).

ANOVAs were performed on the *d*′ and *β* data with the factors of stimulation (tactile–tactile vs. tactile–visual) and masking modality (visual vs. tactile) on the data from the masked interval blocks. The results of the analysis of *d*′ revealed a significant main effect of the masking modality [$F(1,17) = 9.59$, $p < .01$] and a significant interaction between masking modality and stimulation [$F(1,17) = 10.44$, $p<.01$]. A Duncan post-hoc test revealed that in the unimodal tactile condition, the nature of the mask significantly influenced participants' performance ($p < .005$). In particular, participants' responses were significantly less accurate when a tactile mask was presented (1.37 ± 0.18) than when a visual mask was presented (2.14 ± 0.14). However, in the crossmodal tactile–visual condition, the results did not differ significantly as a function of whether the mask was tactile (1.37 ± 0.17) or visual (1.21 ± 0.20). An analysis of the response bias data did not show any effect of the nature of mask [$F(1,17) = 2.64$, $p = .11$], nor any interaction with block type [$F(1,17) < 1$, n.s.].

In order to determine whether participants' performance was significantly affected by the presence of a visual mask in the tactile–tactile condition or whether the effect of block type was due only to the tactile mask we performed an ANOVA on *d*′ on the effect of the visual mask (no interval, empty interval, and visual masked interval). This analysis revealed a significant main effect of the visual mask [$F(2,34) = 7.49$, $p < .001$]. A Duncan post-hoc test revealed a significant difference between the visual masked interval and the other two block types: empty interval and no interval blocks (both *p*s < .005). This result is similar to those obtained in the previous studies of tactile change detection with visual masking (cf. Gallace, Auvray, et al., 2006). The analysis of the response bias data did not show any significant effect of the visual mask ($F < 1$). An ANOVA on *d*′ for the tactile mask data (no interval, empty interval, and tactile masked interval) showed a significant main effect of the presence of the tactile mask [$F(2,34) = 34.42$, $p < .00001$]. A Duncan post-hoc test highlighted a significant difference between the tactile masked interval block and the other two block types: empty interval and no interval blocks (both $p < .005$). The analysis of the response bias data did not show any significant effect of the tactile mask ($F < 1$).

An ANOVA performed on all the RT data (i.e., including both the correct and incorrect responses) with the factors of stimulation and block type highlighted a significant main effect of stimulation [$F(1,17) = 37.48$, $p < .0001$], with participants responding more rapidly when both of the stimulation patterns were tactile (mean: 1230 ± 53 ms) than when the first pattern was tactile and the second was visual (mean: 1552 ± 62 ms). This result may reflect a rapid resumption of interrupted visual search for the intramodal case (e.g., see Lleras, Rensink, & Enns, 2005). It may also reflect a non-spatial modality-driven attentional capture (e.g., Rodway, 2005; Spence, Nicholls, & Driver, 2001; Turatto, Benso, Galfano, & Umiltà, 2002; Turatto, Galfano, Bridgeman, & Umiltà, 2004). In particular, Turatto et al. (2004) showed that the onset of an irrelevant visual or tactile stimulus leads to faster response times for the discrimination of a following target presented in the same sensory modality as compared to a different sensory modality. The analysis did not reveal any main effect of block type, nor interaction between block type and stimulation [both Fs < 1].

The results of Experiment 2 show that change blindness can be elicited with a similar magnitude in both the unimodal tactile and crossmodal tactile–visual conditions. The results also revealed that performance was better overall in the unimodal tactile than in the crossmodal condition. This may reflect the fact that in the tactile–visual condition, the crossmodal presentation of the stimulus patterns implies a weaker form of apparent motion than in the unimodal condition (e.g., Harrar et al., 2005). Thus, participants' performance in the crossmodal condition would not have been favoured by the presence of any apparent motion transients as compared to performance in the unimodal tactile condition. Furthermore, the nature of the mask had a significant effect on performance. In the tactile–visual condition, the tactile and visual masks both influenced participants' performance to a similar degree. By contrast, in the unimodal tactile condition, participants' performance was more deleteriously affected by the presentation of a tactile mask than by the presentation of a visual mask. This difference can also be explained by the fact that since motion transients are stronger when the stimuli belong to the same sensory modality, the masks presented within the same modality as the two to-be-compared displays would be expected to have a more detrimental effect on change detection performance.

It should also be noted that in Experiments 1 and 2, there was a significant effect of the number of stimuli presented. In particular, the participants responded less accurately when the two to-be-compared displays were composed of three stimuli than when they were composed of just two stimuli. Similar results have been reported in previous studies of unimodal visual and tactile change detection (Gallace et al., 2006a). Such findings may be related to research on short-term memory (STM) that has shown that the storage of information in visual STM is very limited. For example, observers are able to remember the identity of about four or five letters out of 12 or more, even if they have the impression that they can see all the letters. It thus seems that there is a kind of attentional "bottleneck" which limits the transfer of information from STM into long-term memory: only a fraction of the information available in a complex scene can be transferred into visual storage for later comparison or report (see Coltheart, 1980, 1983; Haber, 1983; Sperling, 1960).

8. Experiment 3

In the third experiment, we investigated change detection performance under conditions where both of the patterns were presented visually. A preliminary control study was conducted using the same duration of stimulus presentation as in Experiments 1 and 2. 6 participants (2 females and 4 males, with ages ranging from 19 to 30 years, mean of 23.2 ± 7 years) completed the experiment. Analysis of the d' data revealed that participants' performance was overall near-perfect across all block types: no interval (mean: 3.4), empty interval (mean: 3.6), and masked interval (mean: 3.3) (corresponding β values were 0.79, 0.86, and 0.86). Consequently, in order to investigate the effect of block type on unimodal visual change detection, in Experiment 3 we increased the difficulty of the task by shortening the duration of the two to-be-compared displays and increasing the number of stimuli presented.

9. Methods

The materials and procedure were similar to those reported for Experiments 1 and 2 with the following differences. The patterns of stimulation consisted of either 4 or 5 LEDs presented equiprobably from each of the eight possible bodily locations. Additional vibrotactile stimuli used for the masking conditions were added at the same locations as the LEDs. The eight tactors and LEDs were placed at the following positions on the body surface: (1) on the waistline, to the right of the body midline; (2) on the waistline, on the body midline; (3) on the left hip; (4) on the left wrist; (5) and (6) on the upper and lower parts of the right thigh; (7) on the middle of the left thigh; (8) Just under the left knee. The two to-be-compared patterns of stimulation consisted of visual displays presented for 100 ms each. The participants completed four blocks of trials: no interval, empty interval, masked interval, and mudsplash interval with the order of presentation being randomly varied across the participants. In the first block, the two patterns of stimulation were presented one directly after the other. In the second block, the two patterns were separated by a 350 ms empty interstimulus interval. In the third block of trials, the two patterns were separated by a 100 ms empty interstimulus interval, followed by a 150 ms mask, and then a second 100 ms empty interstimulus interval. In half of the trials, the mask consisted of the illumination of all of the LEDs on the participants' body, while on the other half of trials, it consisted of the activation of all of the tactors instead. In the fourth block, the two patterns were separated by a 100 ms empty interstimulus interval, followed by a 150 ms "mudsplash", and then by a second 100 ms empty interstimulus interval. In half of the trials, the mudsplash consisted of the illumination of one of the LEDs on the participants' body, while on the other half of trials, it consisted of the activation of one of the tactors instead. The position of the tactor or LED constituting the mudsplash was randomized across the trials. It should be noted that the mudsplash condition was added in order to investigate whether a single distractor could attract participants' attention to a specific spatial location and consequently have a more detrimental effect on participants' performance as compared to the masked interval condition.

10. Participants

Fourteen participants (5 females and 9 males) took part in this experiment. Their ages ranged from 20 to 33 years (mean: 24.7 ± S.D. of 4.6 years). All of the participants had normal or corrected to normal vision and reported normal tactile perception. They received a five pound (UK Sterling) gift voucher in return for their participation. The experiment took approximately 30 min to complete.

11. Results and discussion

The trials in which participants failed to make a response before the trial was terminated (<3% of trials overall) were not included in the data analyses. An ANOVA was conducted on the d' and β data with two factors: block type (no interval, empty interval, masked interval, and mudsplash interval) and number of stimuli composing the display (4 vs. 5). The analysis of d' revealed a significant main effect of block type [$F(3,39) = 29.67$, $p < .0001$], a significant main effect of the number of stimuli [$F(1,13) = 18.77$, $p < .001$], but no significant interaction between these two factors ($F < 1$). A Duncan post-hoc test on the block type factor revealed a significant difference in performance between all four block types (all ps < .005). Participants' performance was more accurate in the no interval block (mean: 2.7 ± S.E. of 0.1), followed by the empty interval (mean: 2.1 ± 0.1), the mudsplash interval (mean: 1.7 ± 0.1), and then the masked interval blocks (mean: 1.2 ± 0.1) (see Fig. 4). The analysis of the response bias data β revealed a marginal effect of block type [$F(3,39) = 2.66$, $p = .55$], no effect of the number of stimuli, nor any interaction between these two factors (both Fs < 1).

An ANOVA was performed on the d' and β data as a function of the Masking modality (visual vs. tactile) and block type (mudsplash vs. masked interval). The ANOVA on d' showed a significant effect of the masking modality [$F(1,13) = 74.96$, $p < .0001$]. Participants' performance was worse with a visual mask (mean: 0.7 ± 0.2) than with a tactile mask (mean: 2.1 ± 0.1). The analysis also showed a significant interaction between masking modality and block type [$F(1,13) = 24.29$, $p < .001$]. A Duncan post-hoc test revealed a significant difference among all the terms in the interaction (all ps < .001) except between the masked interval with a tactile mask and the mudsplash interval with a tactile mudsplash. The analysis of the response bias data did not reveal any significant effect of masking modality [$F(1,13) = 2.45$, $p = .13$], nor interaction with stimulation ($F < 1$).

In order to determine whether participants' performance was significantly affected by the presence of tactile distractors (mask or mudsplash), or whether the effect of block type

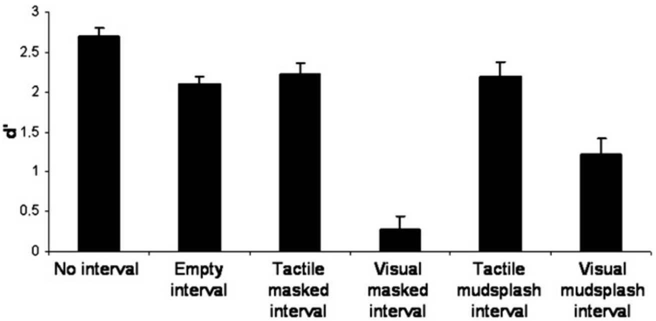

Fig. 4. Participants' mean performance (d') for the six interval conditions: no interval, empty interval, tactile masked interval, visual masked interval, tactile mudsplash, and visual mudsplash (Experiment 3). Error bars represent the standard errors of the means.

was only due to the visual distractors, we performed an ANOVA on d' for the four block types: no interval, empty interval, tactile mudsplash interval, and tactile masked interval, with (for the latter two blocks) only the data for the tactile distractors. The analysis showed a significant main effect of block type [$F(3,39) = 3.05$, $p < .05$]. However, Duncan post-hoc tests showed a significant difference between the no interval condition and the other three block types: empty interval, tactile masked interval, and tactile mudsplash interval (all ps < .005), but not between these three latter conditions. The analysis of the response bias data revealed a marginal effect of block type [$F(3,39) = 2.88$, $p = .053$]. A Duncan post-hoc test only highlighted a significant difference between the no interval and the empty interval conditions ($p < .05$). A similar ANOVA was conducted on the d' data for the four block types: no interval, empty interval, visual mudsplash interval, visual masked interval, with in the latter two blocks only the data for the visual distractors. The analysis showed a significant main effect of block type [$F(3,39) = 47.29$, $p < .0001$]. A Duncan post-hoc test showed a significant difference between all the terms involved in the interaction (all ps < .005). The analysis of the response bias data did not show any significant effect of block type [$F(3,39) = 1.23$, $p = .30$].

An ANOVA performed on the raw error data with the factors of block type and presence versus absence of change between the two patterns of stimuli composing the displays revealed a significant main effect of the Presence versus absence of change [$F(1,13) = 15.03$, $p < .001$]. Participants made more errors when there was a change (26.5% failure to detect a change) than when there was no change (10.7% false alarm rate). The analysis did not show any interactions with block type ($F < 1$).

A final ANOVA performed on the RT data with the factor of block type showed a significant effect of block type [$F(3,39) = 12.28$, $p < .01$]. Duncan post-hoc tests revealed that RTs were significantly different between the continuous condition on the one hand and the masked and mudsplash conditions on the other hand (both ps < .05). There was also a significant difference between the mudsplash and mask conditions ($p < .05$). Participants responded more rapidly in the no interval block (mean: 654 ± S.E. of 36 ms), followed by the empty interval (mean: 758 ± 38 ms), the mudsplash interval (mean: 933 ± 75 ms), and then the masked interval blocks (mean: 934 ± 76 ms).

The results of Experiment 3 show that change blindness can be elicited under conditions of unimodal visual stimulation. The presence of an empty interval between the two to-be-compared patterns resulted in a reduction in participants' performance as compared to the continuous presentation condition. This result is consistent with a gradual decay of information in STM (e.g., Sperling, 1960, 1963; see also Di Lollo, 1980). Furthermore, the presence of distractors between the two-to-be compared patterns significantly impaired participants' performance as compared to the continuous and the empty interval conditions. It should be noted that the masked interval had a more detrimental effect on participants' performance than the mudsplash interval. In fact, the performance with the visual mask was close to $d' = 0$, indicating that participants could hardly judge the occurrence of a change in the visual stimuli (see Fig. 4). Thus, the use of a single distractor to attract participants' attention to a specific spatial location was less effective in impairing change detection performance than a global mask. Importantly, in the masked and mudsplash intervals, the change blindness effect was elicited by means of the visual distractors. The tactile masks and mudsplashes did not significantly impair participants' performance relative to the empty interval condition.

12. General discussion

In the study reported here, we investigated people's ability to detect positional changes between simple patterns presented in either the same or different sensory modalities. The stimuli were presented on participants' bodies by means of tactors and LEDs placed at exactly the same bodily locations. The two to-be-compared stimulus patterns were presented consecutively, separated by an empty interval, or else separated by a masked interval. Three main results emerged from this study. First, we demonstrated that people can detect changes crossmodally; that is, under normal viewing conditions, people were able to detect positional changes between successive patterns presented in different sensory modalities (vision and touch). The second main result to emerge from the present study was the demonstration of crossmodal change blindness: performance in detecting changes across different sensory modalities was impaired when a mask was introduced between the two to-be-compared patterns. Third, we found asymmetries as a function of the different conditions of stimulus presentation: performance was better overall in the unimodal than in the crossmodal conditions.

The most important of these three results was that participants' ability to detect changes between the two displays presented in different sensory modalities was impaired by the presentation of both unimodal tactile and unimodal visual masks. This result therefore shows that change blindness is not a strictly unimodal phenomenon, but that it can also be elicited crossmodally. The presence under normal viewing conditions of crossmodal apparent motion, although weaker than the unimodal variety (e.g., Harrar et al., 2005) may explain the fact that crossmodal change detection was impaired when some form of disruption occurred between the two displays.

The second important result to emerge from the present study was that under normal viewing conditions, the participants were able to detect the presence of positional changes when the first stimulus pattern was tactile and the second visual or vice versa. The fact that the participants in the present study were able to detect crossmodal changes provides support for the view that certain of the processes underlying the encoding of spatial positions are multisensory/amodal in nature. According to this view, the spatial information acquired through a given sensory modality is not stored exclusively in a format specific to the modality of presentation of the stimuli. Instead, some properties are extracted and held in an abstract or amodal format (e.g., see Abravanel, 1981). Indeed, in order to detect the position of a change occurring crossmodally, the format in which the two to-be-compared patterns are encoded should be similar enough to allow a direct comparison. It could also be hypothesized that the patterns are encoded according to a modality-specific format related to the sensory modality of the first pattern that was presented. However, if this had been the case, we should have found an asymmetry in participants' performance as a function of the nature (i.e., modality) of the mask presented. That is, the modality of the mask should have interfered with performance more when it matched the modality of the first pattern (cf. Soto-Faraco et al., 2002). In our experiments, the similar effects of the visual and tactile masks on both visual–tactile and tactile–visual stimulus presentations favour the idea of a multisensory/amodal code instead. This view can also be related to the literature on visual STM in terms of previous suggestions that the information from a visual scene that is stored for a later report or comparison is typically represented in an abstract non-visual code (see Irwin & Andrew, 1996, for a review).

It should also be noted that the nature of the task used in the present study may have favoured a multisensory/amodal encoding of the spatial position of the target stimuli. Indeed, participants may have used an abstract code simply because this was what was required by the task. On a related note, it will be interesting for future research to investigate the role of the frame of reference used to encode the locations of the stimuli in modulating performance. Pylyshyn (2005) emphasized that in vision we do not have a unitary representation of space in an allocentric frame of reference. On the contrary, we have a large number of different representations of spatial locations within different frames of reference. Correspondingly, Snyder et al. (2002) showed separate activations in the parietal cortex depending on whether the visual spatial information was body-centered (e.g., information for the control of gaze) or world-centered (e.g., information for navigation and other tasks that require an absolute frame of reference). It will thus be interesting to vary the frame of reference in which visual stimulation is presented. For example, the visual and tactile stimuli could be presented to participants in different spatial positions but refer to the same bodily location, by forcing participants to view the visual stimuli by means of mirror reflection.

It might be argued that the locations of the stimuli on the participants' body could have favoured a linguistic encoding of spatial position (i.e., "the stimulus was displayed on my left ankle"; see Kemmerer, 2006, for a review). In order to investigate the extent to which participants used a verbal code, it will be interesting in future research to use a shadowing task or a verbal interference dual-task in order to diminish the verbal resources that the participants may use for the crossmodal change detection task (for the influence of a concurrent verbal task on tactile recall accuracy, see Miles & Borthwick, 1996; for the influence of a concurrent verbal task on change detection in touch, see Mahrer & Miles, 2002; in the visual sensory modality, see Simons, 1996; although see Hollingworth, 2003; VanRullen & Koch, 2003; Vogel, Woodman, & Luck, 2001). However, it should be noted that a recent study by Newell, Woods, Mernagh, and Bülthoff (2005) has shown that performance in a crossmodal visual and haptic comparison of real-world scenes was not impaired by a concurrent articulatory suppression task. It should also be noted that in our experiments, the interval between the two to-be-compared patterns may actually have been short enough to prevent participants from verbally coding two or three bodily locations. Indeed, if the participants were to have used a verbal code, they must have encoded the first pattern, probably before the onset of the second pattern, in order to make a comparison. Relevant to this issue are the results of a study by Le Clec'H et al. (2000). In their experiments, participants were presented with written or spoken names of body parts. The average response time for determining whether or not one body part was higher than the shoulder of a standing person was more than 860 ms. Given that in our study the duration of stimulus presentation was set at 600 ms and the interval between the two consecutive patterns was 0 or 250 ms, on the basis of Le Clec'H et al.'s data, it would appear unlikely that participants in our experiments used a verbal code to perform the task.

In the present study, we found differences in performance as a function of the different conditions of stimulus presentation. Performance was most accurate overall in the unimodal visual condition. Performance was also better overall in the unimodal tactile than in the crossmodal tactile–visual condition; and better in the visual–tactile condition than in the tactile–visual condition. Furthermore, the nature of the mask had a significant influence on the pattern of performance observed. In the crossmodal tactile–visual and visual–tactile conditions, the tactile and visual masks both influenced participants' performance to a similar degree. By contrast, in the unimodal tactile condition, participants' performance was more deleteriously affected by the presentation of a tactile mask than by the presentation of a visual mask. In addition, in the unimodal visual condition, participants' performance was only affected by the presentation of a visual mask. The influence of the mask was explained by the fact that, as motion transients appear to be stronger when generated by stimuli belonging to the same sensory modality, the masks presented within the same modality as the two to-be-compared displays would be expected to have a more detrimental effect on change detection performance (cf. Allen & Kolers, 1981).

However, these asymmetries may reflect the fact that certain of the information is stored in a modality-specific format. They also suggest that the visual and haptic systems have different encoding/memory limitations (e.g., Gallace, Tan, & Spence, 2006b; Mahrer & Miles, 2002). Thus, some of the information may be coded in terms of a modality-specific frame of reference (i.e., retinotopic for vision), accounting for the better performance obtained in the unimodal as compared to the crossmodal change detection task. Additionally, the information required to compare the visual and tactile stimuli presented in the display appears to interact at some level of information processing. Relevant to this issue are the results of a functional magnetic-resonance imaging (fMRI) study by Downar, Crawley, Mikulis, and Davis (2000) concerning auditory, visual, and tactile change detection. This study revealed the existence of a distributed cortical network involved in the detection of changes in the sensory 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 association cortices, as well as multimodally-responsive areas, comprising a right-lateralized network including the temporo-parietal junction, inferior frontal gyrus, insula, left cingulate, and the supplementary motor areas. These results suggest that although some of the processes underlying the detection of change can be modality-specific, at least certain of these processes are also multisensory.

In summary, the results of the three experiments reported in the present study further highlight the differences and the similarities between the change blindness effects reported previously within vision and touch. On the one hand, the asymmetries found as a function of the conditions of stimulus presentation confirmed that the visual and haptic systems have different encoding/memory limitations. On the other hand, the possibility of eliciting change blindness across different sensory modalities using the new methodology highlighted in the present study supports the view that some similar mechanisms may contribute to the change blindness effects observed within the visual, tactile and auditory modalities (see Downar et al., 2000) and the existence of crossmodal links in spatial attention, both endogenous and exogenous (Driver & Spence, 2004; Spence et al., 2004), that operate on these spatial representations.

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