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Attentional blink and selection in the tactile domain

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Brief tactile presses stimulated the index and middle fingers of the right and left hands. The stimulation on each hand consisted of a triplet of presses. Each triplet was composed of a brief press to one finger (e.g., the middle finger), followed by a brief press to the other finger (e.g., the index finger), and by a final simultaneous press to both fingers of a given hand. With equal probability, a triplet could begin with the index or middle finger, and either 360 ms or 800 ms later another triplet stimulated fingers on the other hand. The task was to indicate which finger was stimulated first in each triplet. In four experiments, response accuracy to the second triplet revealed an attentional blink in taction, that is, responses were less accurate at the short triplet–triplet interval than at the long triplet–triplet interval. This effect was substantially reduced when the first triplet could be ignored.

Even with little or no training, most observers have the remarkable ability to identify a visual target when it is embedded in a rapid serial visual presentation (RSVP) stream of spatially overlapping distractors displayed at rates of 10 items/s (e.g., Potter, 1976). Under optimal conditions, some

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observers can even identify well-learned targets presented at up to 100 items/s (Sperling, Budiansky, Spivak, & Johnston, 1971). When identification is required for two targets, which we will designate as T1 and T2, respectively, identification of T2 is however often impaired relative to T1 or to a control condition in which only T2 is to be reported. This phenomenon occurs even when the rate of presentation is as slow as 7–10 items/s (e.g., Arnell & Jolicœur, 1999), and is typically observed when the stimulus–onset asynchrony (SOA) between T1 and T2 is shorter than 500 ms. Furthermore, the duration of the effect appears to depend on the time spent processing T1 (e.g., Jolicœur, 1999a; Jolicœur, Dell'Acqua, & Crebolder, 2000).

Several studies suggest that the cause of the AB resides at a postperceptual stage of processing of T2, namely, beyond the state at which T2 and the items composing the RSVP stream have been fully identified. Support for this view has come from AB paradigms using the RSVP of words. Using these paradigms, T2 report accuracy has been shown to be a function of the semantic relationship between T1 and T2, with higher T2 identification accuracy under conditions in which T1, or a distractor following T1 and preceding T2, was semantically related to T2 (Isaak, Shapiro, & Martin, 1999; Juola, Duvuru, & Peterson, 2000; Maki, Frigen, & Paulson, 1997; Shapiro, Driver, Ward, & Sorensen, 1997). Consistent with the behavioural evidence, full identification of a missed T2 during the AB has also been supported by studies using electrophysiological methods. Vogel, Luck, and Shapiro (1998, Exp. 2, p. 1662) have shown that, during the AB, N400 responses to missed T2 words were preserved in the event-related potential time-locked to T2 onset (see also Rolke, Heil, Streb, & Hennighausen, 2001). A preserved N400 response during the AB suggests that T2 was processed to the level of meaning during the AB (e.g., Kutas & Hillyard, 1980). In a different experiment (Exp. 4, p. 1666), Vogel et al. have found a reduced P300 response to an infrequent T2 letter stimulus presented during the AB (Exp. 4, p. 1666). Although different interpretations have been proposed for the P300 response (e.g., Donchin, 1981; Verleger, 1988), there is a general consensus that the P300 represents electrophysiological evidence for the updating of information in short-term memory (STM; Donchin & Coles, 1988; Johnson, 1986). Jointly with the preservation of N400 responses, the evidence of suppressed P300 responses during the AB have thus been taken to reflect a failure in the transfer of a postperceptual T2 to STM, a memory system hypothesised to support the overt report of T2 a few seconds later from its presentation (Chun & Potter, 1995; Dell'Acqua, Jolicœur, Pesciarelli, Job, & Palomba, 2003; Vogel et al., 1998). In vision, transfer, or consolidation, into STM appears to require a serial operation that constitutes a bottleneck in the processing of T2. When consolidation mechanisms are busy with T1 processing, the consolidation of a T2 presented shortly after T1 is hypothesised to be momentarily postponed.

This delay in the consolidation of T2 explains the loss of T2 at short T1–T2 lags. Studies in which the masking parameters of T1 and T2 have been systematically manipulated have indeed suggested that the representation of T2 that has not already reached the status of STM trace is likely more susceptible to degradation (or substitution; Dell'Acqua, Pascali, Jolicœur, & Sessa, 2003; Giesbrecht & Di Lollo, 1998) by trailing items, compared to those in STM.

Recently, an interesting question concerning the AB phenomenon has focused on whether the AB is specific to vision, as opposed to the manifestation of a supramodal capacity limitation in the information processing system. In the supramodal view, the processing of stimulation from different sensory modalities would require access to one or more common amodal central mechanisms. These common central mechanisms would mediate the integration of multiple sensory inputs into a centrally unified stream of behaviour.

One way to study this issue, in the context of the AB, has been to explore the AB effect in sensory modalities other than vision. Several studies have investigated the AB effect in audition, with mixed results. Using the rapid auditory presentation (RAP) of stimuli, some researchers have found auditory AB effects (Arnell & Jolicœur, 1999; Mondor, 1998), whereas others have not (Potter, Chun, Banks, & Muckenhoupt, 1998). Chun and Potter (2001) attempted to sort out this inconsistency and suggested that nonvisual AB effects tend to be found only when there is a task switch (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995) associated with the processing of the two targets. That is, Chun and Potter (2001; see also Potter et al., 1998) proposed that pure (i.e., not affected by switch effects) AB effects are typical of the visual modality, whereas other modalities would in principle be insensitive to AB effects if there were complete homogeneity in the features allowing the selection of the two targets, and in the features reported from the two targets at the end of each trial. More recent work, however, has established important exceptions to Chun and Potter's (2001) proposal, insofar as pure auditory AB effects have been found by Soto-Faraco and Spence (2002) and Arnell and Larson (2002). Soto-Faraco and Spence embedded T1 and T2 digits in two concurrent streams of letters presented in the visual modality and in the auditory modality. T1 and T2 were presented in either modality unpredictably, and in the same spatial location. In this design, there were equiprobable conditions in which targets were presented in the same modality (either the visual or the auditory modality), or in different modalities (varying unpredictably the modality order). Participants in this experiment were instructed to report T1 and T2 with no speed pressure, and independently of order or modality of presentation, typing them on the keyboard of the computer used for stimuli presentation. Interestingly, whereas no AB effects were found in the crossmodal conditions, sizeable AB effects were found both in the unimodal visual condition and in the unimodal auditory condition. Of relevance in this context, analogous unimodal AB effects have been reported by Arnell and Larson, who asked participants to monitor concurrent visual and auditory streams of stimuli for the presence of one of two prespecified letters (i.e., K or L). In partial contrast with the results of Soto-Faraco and Spence, however, an AB effect was found by Arnell and Larson also in the crossmodal condition in which a visual T2 followed the presentation of an auditory T1.

Contrary to the many studies mentioned above that focused on AB effects in vision and audition, pure AB effects in taction have been the object of much less investigation, with only one published paper focusing specifically on this issue. Hillstrom, Shapiro, and Spence (2002) presented participants with streams of briefly presented (i.e., 150 ms, on average across the experiments) cutaneous vibrations applied to the fingertips. Two target vibrations, T1 and T2, were embedded in each tactile stream. In different trials, T1 and T2 were separated by SOAs ranging from about 100 ms to more than 1 s. In different experiments, T1 and T2 could be selected on the basis of either intensity, duration, frequency, or location, or by a combination of these tactile features. Three of the seven experiments carried out by Hillstrom et al. tested AB effects in the tactile modality, in the absence of various forms of task or feature switches. In these experiments the selection of T1 and T2 occurred on the basis of the same physical feature (intensity, duration, or location, in Exps. 1, 2, and 7, respectively). Furthermore, the features reported from T1 and T2 without speed pressure at the end of each trial were the same (one of two prespecified target frequencies in Exps. 1 and 2; one of two prespecified fingers of a given hand in Exp. 7). In all these conditions, participants reported the prespecified feature from both T1 and T2 on half of the trials, and only from T2 on the other half of the trials. Interestingly, a clear tactile AB effect was found only in Experiment 7, where T1 and T2 were presented separately to the left and right hands in the form of vibrations to either the index finger or thumb. The task was to report which of these two sensory surfaces had been stimulated. In Experiments 1–6 report accuracy for T2 decreased, as SOA was reduced, as much when T1 had to be reported as when T1 could be ignored, and almost as much (although statistically less so) in Experiment 7. In other words, unlike what is typically found in vision, there were strong SOA effects in the ignore-T1 condition.

The source of the SOA effects on ignore-T1 trials could be explained in two not mutually exclusive ways. First, it is possible that T1 masked T2. Second, it is possible that participants could not ignore T1, even when instructed to do so. Given that T1 and T2 often had very similar physical features, it is possible that trying to select T2 led to contingent capture by T1

(Folk, Remington, & Johnston, 1992). Hillstrom et al. (2002) argued that SOA effects on T2 report accuracy in the ignore-T1 condition produced by involuntary encoding of T1 would constitute an AB effect. Usually, however, one defines the AB as the difference in accuracy of report of T2 between the control condition (ignore T1) and the experimental condition (encode T1), which provides unambiguous evidence for an AB when there is a significant difference, at short SOA, between the two experimental and control conditions, and a smaller difference or no difference at long SOA. In the present paper we sought to explore the issue of this reduced AB effect in taction by varying orthogonally two different dimensions related to the sequential tactile stimulation.

In the present designs, T2 consisted of the stimulation of two fingers (index and middle) on either the right or the left hand. The stimulation sequence consisted of a pulse to one finger, followed by a pulse to the other finger, followed by simultaneous pulses to both fingers. With equal probability, the stimulation sequence started with the index or middle finger. A second stimulus sequence of the same type was applied to the other hand after an SOA of either 360 ms or 800 ms. For report-T1 trial blocks, the task was to report which finger was stimulated first, for each sequence. For ignore-T1 trial blocks, the task was to report which finger was stimulated first in the second sequence (T2). In all four experiments in this paper, we found a reliable AB defined in the traditional way as a larger effect of SOA for the report-T1 condition than for the ignore-T1 condition.

In addition, across the experiments, we manipulated the similarity of T1 and T2 on ignore-T1 trials by varying orthogonally two specific dimensions related to their presentation, namely, whether the order of hand stimulation was unpredictable (left–right and right-left trials intermixed at random) versus predictable (blocked), and the similarity of the patterns defining T1 and T2 (identical vs. different). Based on the results of these manipulations we were able to rule out masking factors as the possible cause of the strong lag effects that were found in the ignore-T1 condition of Hillstrom's et al. (2002) designs, and we discovered that the pattern similarity and the predictability of the order of presentation interacted to allow participants to ignore T1 when instructed to do so (something they could not do when each cue was presented in isolation).

EXPERIMENT 1

Method

Participants. A total of 64 students at the University of Padova volunteered to participate in the following experiments, 16 students in each experiment. All were undergraduate or graduate students, with an age ranging from 20 to 32 years. All were naive to the purpose of the experiment, and all reported no deficits in taction.

Stimuli and apparatus. The tactile stimuli were two different triplets of presses applied to the distal pads of the index and the middle fingers. One triplet of presses stimulated the left hand and the other stimulated the right hand. Each press lasted 20 ms. A triplet began with a first press applied to one fingerpad (e.g., of the middle finger), followed by a blank interval of a variable temporal duration (see below). After the blank interval, a second press was applied to the other fingerpad (e.g., of the index finger), followed by a blank interval of the same temporal duration as that of the preceding blank interval. The sequence terminated with a third press applied simultaneously to both fingers. There were two possible patterns of stimulation that differed in terms of which finger was stimulated first (index or middle finger).

The apparatus for the generation of the tactile stimuli consisted of two tactile stimulators, placed on a horizontal surface lying in front of the participant, fitted against the distal pads of the index and middle fingers of each hand. The stimulators were placed symmetrically with respect to the participants' sagittal axis, at a distance of 40 cm of each other. The stimulators were embedded in foam material to reduce the noise generated by their functioning. Each stimulator consisted of a pair of miniaturised solenoids (3 W, 112 V) with a moving cylindrical metallic plunger 1.4 mm in diameter and 50 mm in length. The plunger was oriented perpendicularly to the surface of the skin. The plunger for each stimulator could be activated independently, allowing us to stimulate the index or middle finger of each hand separately. Upon activation, the plunger of a given stimulator moved 2.5 mm and pressed against the skin of the stimulated finger. A 686 CPU controlled the tactile stimulators, the duration and sequencing of the tactile stimuli, as well as a visual monitor that was used to give instructions and feedback to the participants.

Design and procedure. Participants were seated with both arms resting on the table in front of them, facing a computer monitor. On each trial, two tactile stimuli, T1 and T2, were presented in succession, with each stimulus requiring a distinct response. Each trial began with a pair of horizontally arrayed plus signs (+ +) displayed at the centre of the monitor, that remained on the screen during the entire trial. The experiment was self-paced. Participants initiated each trial by uttering the word "go" into a microphone connected to the CPU. After the utterance, a fixed temporal interval of 600 ms elapsed before the presentation of the first triplet (T1) to the fingers of one hand. At one of two possible SOAs (either 360 or 800 ms) following T1, a second triplet (T2) was presented to the fingers of the other hand. On each trial, the probability that a given finger was stimulated first was .25; that is, which hand and which finger of a given hand were stimulated first was random and equiprobable. Responses had to be emitted at the end of the stimuli presentation using the "Z" and "X" keys of the computer keyboard to indicate which finger of the left hand was stimulated first, and the "N" and "M" keys of the computer keyboard to indicate which finger of the right hand was stimulated first. Participants were invited to press the appropriate keys using the same fingers as those subject to the tactile stimulation, maintaining a spatially compatible stimulus–response mapping for the entire duration of the experiment (LEFT HAND: "Z" = middle; "X" = index; RIGHT HAND: "M" = middle; "N" = index). The computer keyboard was placed on the same surface where the tactile stimulators were positioned, with the sets of adjacent "Z&X" keys and "N&M" keys arranged symmetrically with respect to the participant's sagittal axis.

In half of the blocks of trials, participants were instructed to ignore T1 and to respond only to T2 (i.e., by indicating which finger was stimulated first in the T2 triplet). In the other half of the blocks of trials, participants had to respond to both T1 and T2 (i.e., by indicating which finger was stimulated first both in the T1 triplet and in the T2 triplet). When two responses were to be emitted at the end of the trial, no instructions were provided to participants concerning response order. The plus signs displayed at the centre of the screen at the beginning of each trial provided feedback on performance in the previous trial, and acted as a fixation point in the current trial. The left plus sign indicated the performance with the triplet presented to the left hand; the right plus indicated the performance with the triplet presented to the right hand. A plus sign indicated a correct response; a minus sign indicated an incorrect response.

The first portion of the experiment was dedicated to practice. Participants performed four blocks of 8 trials in each T1 condition (i.e., ignore-T1 vs. report-T1). In the first four blocks of practice trials, the SOA between T1 and T2 was always long. In the second four blocks, T2 was presented at both the long and short SOAs. During the practice phase, the blank temporal duration separating the presses in the T2 triplet was adjusted to keep T2 localisation accuracy off ceiling and above floor, while the blank temporal duration separating the presses in the T1 triplet was maintained constant at 80 ms. Mean accuracy in the task on T2 was computed at the end of each block only for trials at the long SOA. The blank duration for T2 (set initially to 100 ms) was lengthened by 10 ms if accuracy was below 60%, or shortened by 20 ms if accuracy was above 85%. The staircase procedure continued throughout the entire experiment, using the mean accuracy level on T2 at the long SOA in the previous block of trials in a given T1 condition (that is, there were two concurrent, independent, interleaved staircases, one for ignore-T1 trials and one for report-T1 trials), to adjust the T2 blank interval duration for the next block of trials in the same T1 condition. Within each block of trials, the blank interval duration for T2 was held constant. At the end of the practice session, the instructions were repeated, and each participant performed experimental trials organised into eight blocks of 32 trials each. Half of the participants started with four blocks of ignore-T1 trials, followed by four blocks of report-T1 trials. For the other half of the participants, this order was reversed. Levels of SOA, T1 starting location, and T2 starting location were fully crossed within each block of trials.

Results

The analyses concentrated on the proportion of correct responses to T1 starting location (in the report-T1 condition), on the proportion of correct responses to T2 starting location, and on d' (Green & Swets, 1974) in the localisation task on T2 calculated by treating one stimulus category (i.e., index finger) as signal, and the other stimulus category (i.e., middle finger) as noise. Mean proportion of correct responses and d' values were analysed using the analysis of variance (ANOVA), in which SOA and T1-task (in the analyses of T2 responses) were treated as a within-subject variables. A further analysis was carried out on the temporal duration of the blank interval elapsing between the single presses composing the T2 triplet. These durations, averaged over blocks for each participant, were submitted to an ANOVA in which T1-task was treated as a within-subject variable.

Responses to T1. The mean proportion of correct responses to T1 at the short SOA and long SOA was .76 and .75, respectively. These values did not differ significantly ($F < 1$).

Responses to T2. The mean proportion of correct responses to T2, as a function of SOA, and as a function of the task performed on T1 is shown in Figure 1 (top-left panel).

The ANOVA performed on the mean proportion of correct responses to T2 revealed a significant effect of SOA, $F(1, 15) = 159.9$, $p < .001$, a significant effect of the T1-task, $F(1, 15) = 18.9$, $p < .001$, and a significant interaction between these two variables, $F(1, 15) = 10.2$, $p < .007$. The SOA effect was significant when the results from the ignore-T1 condition were analysed separately, $F(1, 15) = 80.5$, $p < .001$. Analogous results were obtained in the analysis carried out on d'. The ANOVA revealed a significant effect of SOA, $F(1, 15) = 260.0$, $p < .001$, a significant effect of

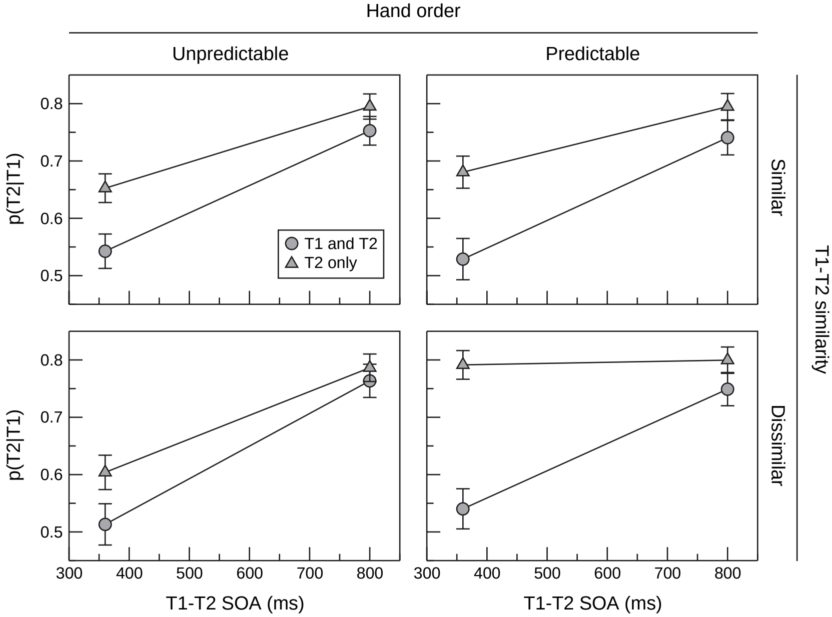

Figure 1. Top-left panel: Results from Experiment 1 (unpredictable hand order, T1 same as T2). Mean proportion of correct responses to T2, as a function of SOA for ignore T1 vs. report-T1 trial blocks. Vertical bars show the standard error of the mean. Top-right panel: Results from Experiment 2 (predictable hand order, T1 same as T2). Bottom-left panel: Results from Experiment 3 (unpredictable hand order, T1 and T2 dissimilar). Bottom-right panel: Results from Experiment 4 (predictable hand order, T1 and T2 dissimilar).

the T1 task, $F(1, 15) = 11.5$, $p < .001$, and a significant interaction between these two variables, $F(1, 15) = 10.7$, $p < .006$. The SOA effect was significant when the results from the ignore-T1 condition were analysed separately, $F(1, 1) = 115.0$, $p < .001$.

Rate of stimulation. The mean blank interval durations were 68 ms in the ignore-T1 and 80 ms in the report-T1 condition. These values differed significantly, $F(1, 15) = 5.5$, $p < .05$. A slightly longer interval was required to bring performance in the desired range when T1 had to be reported. Interestingly, although characterised by easier stimulation conditions (a longer interval between pulses would make it easier to determine which one came first), report-T1 trials nonetheless produced a worse overall performance than ignore-T1 trials. This is reassuring in light of the possible risk that the observed pattern of results could have been actively modulated by the independent manipulation of the staircasing algorithm across ignore-T1 and report-T1 conditions used in Experiment 1.

Discussion

The results were clear-cut: The ability to report which finger was stimulated first on the second hand to be stimulated declined as the SOA between hands was reduced, and this decrease was larger when a report had to be made for both hands (T1 and T2) than the first stimulated hand could be ignored (report T2 only, ignore T1). This overall pattern of results demonstrates a purely tactile AB effect in the absence of task switching, because the same task and selection criteria were used for both targets.

EXPERIMENT 2

One aspect of the results of Experiment 1 that was expected based on the results reported by Hillstrom et al. (2002) was that, when T1 could be ignored, performance on T2 was nonetheless clearly reduced as SOA was shortened. In the visual domain, one typically finds relatively small effects of SOA on accuracy of report of T2 when T1 can be ignored. We hypothesised that the unpredictability of the hand of first stimulation might have made it more difficult for participants to ignore T1 and concentrate only on T2. For this reason, in Experiment 2 the hand that was stimulated first was fixed for the entire duration of the test session (e.g., left first, right second), and which hand was stimulated first was counterbalanced across participants. Thus, participants could now predict which hand would be stimulated first and which would be stimulated second. We expected that this might help them to focus on T2 in blocks of trials where they could ignore T1. This in turn should reduce the magnitude of the SOA effect for T2 in the ignore-T1 condition.

Method

Stimuli and apparatus. The same tactile stimuli as those used in Experiment 1 were used in Experiment 2.

Design and procedure. The design and procedure were the same as in Experiment 1 except that which hand was stimulated first was the same on all trials for any given participant. For half of the participants, the order of stimulation was left–right; for the other half the order was right–left.

Results

Responses to T1. The mean proportion of correct responses to T1 at the short SOA and long SOA was .73 and .75, respectively. The small difference between these values was significant, $F(1, 15) = 7.2$, $p < .05$.

Responses to T2. The mean proportion of correct responses to T2, as a function of SOA, and as a function of the task performed on T1 is reported in Figure 1 (top-right panel). An ANOVA performed on the mean proportion of correct responses to T2 revealed a significant effect of SOA, $F(1, 15) = 72.6$, $p < .001$, a significant effect of the T1 task, $F(1, 15) = 41.9$, $p < .001$, and a significant interaction between these two variables, $F(1, 15) = 13.0$, $p < .003$. The SOA effect was significant when the results from the ignore-T1 condition were analysed separately, $F(1, 15) = 22.7$, $p < .001$. The ANOVA carried out on d' revealed the same pattern of results: There was a significant effect of SOA, $F(1, 15) = 61.7$, $p < .001$, a significant effect of the T1 task, $F(1, 15) = 29.0$, $p < .001$, and a significant interaction between these two variables, $F(1, 15) = 8.7$, $p < .02$. The SOA effect was also significant when the ignore-T1 condition was analysed separately, $F(1, 15) = 23.9$, $p < .001$.

Rate of stimulation. The mean blank interval duration was 90 ms in the ignore-T1 and 82 ms in the report-T1 condition. These values differed significantly, $F(1, 5) = 12.5$, $p < .005$. These values were reversed compared with what was found in the other three experiments, which suggests that small differences in the mean blank interval do not have large effects on the pattern of results associated with the SOA manipulation, but could explain why the difference between the ignore-T1 and report-T1 conditions is larger in Experiment 2 than in Experiment 1.

Discussion

As in Experiment 1, the most important results were clear-cut: There was a larger decrease in report accuracy of the second tactile target as SOA was reduced when participants had to process the first tactile target than when they could ignore the first target. Therefore, as in Experiment 1, the results provide evidence for a purely tactile AB effect affecting stimulus location processing and shows that the results can be replicated under somewhat different experimental conditions, which resemble closely the conditions of Experiment 7 of Hillstrom et al. (2002).

Contrary to our expectations, however, there was little effect of fixing the order of stimulation across the two hands. In Experiment 1 the order of stimulation of the left and right hands was random, whereas the order was constant in Experiment 2. As can be seen in the top two panels of Figure 1, the pattern of results observed in the two experiments was nearly identical. In particular, fixing hand order did not attenuate the SOA effect found in the ignore-T1 condition. It appears that, for our stimulation conditions, it is difficult to ignore a pattern of stimulation on a different hand as the one to be reported, even when the participant knows which hand will be stimulated first (and is to be ignored) and which hand will be stimulated second.

EXPERIMENT 3

The results of Experiments 1 and 2 revealed an interesting inability to filter out unwanted irrelevant tactile stimulation. We found a significant reduction in the probability of correct report of T2 as SOA was reduced, even when T1 could be ignored. Furthermore, this SOA effect was found regardless of whether the order of stimulation of the left and right hands was unpredictable or predictable. With the patterns of stimulation that we used, it appears that it was not possible to ignore completely the first burst of stimulation, which in turn likely caused some interference with the processes mediating the report of T2.

Spence and McGlone (2001) provided evidence for automatic capture of tactile attention by spatially nonpredictive tactile cues. These authors investigated the ability of participants to localise which of two parts of the hand (either the thumb or the index finger) of either hand received a burst of tactile stimulation. The target tactile stimulus was preceded at SOAs of 200 ms, 300 ms, or 400 ms by a burst of tactile stimulation (i.e., the cue) applied to both fingers concurrently. The cue was applied with equal probability to the hand opposite to the one stimulated by the target, or to the same hand as that stimulated by the target. Interestingly, when the nonpredictive cue was presented to the same hand as that stimulated by the target burst, the response time to localise the stimulated finger was shorter compared to the different condition in which target and cue were presented to different hands. These results from Spence and McGlone suggest that a tactile stimulus may attract attention to the location of the stimulation. Perhaps some, or all, of the SOA effects in the ignore-T1 trials of Experiments 1 and 2 could be due to a reflexive orienting of spatial tactile attention, driven by the representation of the first to-be-ignored stimulus.

On the other hand, research in the visual domain suggests that attentional control settings can modulate the degree to which particular stimuli control involuntary orienting (Folk et al., 1992). In their view, a distractor stimulus is more likely to capture attention if it shares a feature value with a target stimulus on a dimension that is used to select the target among non targets. They call this effect contingent capture. In addition to possible reflexive tactile orienting, we hypothesised that contingent capture may have also played a role in Experiments 1 and 2 because the patterns of stimulation for T1 and T2 were identical. Thus, it may have been difficult to avoid processing T1 because it corresponded in all ways (except spatial location) to the stimulation anticipated for the second task. In order to test this possibility, in Experiment 3 we introduced a difference in the pattern of tactile stimulation between T1 and T2. This patterning difference was designed to provide an additional cue that could be used to filter out the unwanted T1 signals in ignore-T1 trials.

In the present experiment, as in Experiment 1, the order of presentation of T1 and T2 to the two hands was unpredictable. Thus, the only difference between Experiment 1 and Experiment 3 was the difference in the T1 pattern during ignore-T1 blocks, allowing us to compare the results of the two experiments directly. T1 in the ignore-T1 condition was composed of a single press applied simultaneously to the index and middle fingers of the same hand, making it temporally and spatially dissimilar from T2. In the report-T1 condition of Experiment 3, T1 and T2 were still composed of triplets of presses (as in Experiments 1 and 2).

Method

Stimuli and apparatus. In the report-T1 blocks of trials of Experiment 3, the tactile stimulation was identical to the stimulation used in the previous experiments (i.e., both T1 and T2 were sequential triplets of brief presses). Unlike in Experiments 1 and 2, the tactile stimulation used as T1 in the ignore-T1 blocks of trials of the present experiment was composed of a single 20 ms press applied simultaneously to the middle and index fingers of the same hand.

Design and procedure. The design and procedure were the same as in Experiment 1. In particular, as in Experiment 1, the order in which T1 and T2 were applied to the hands was unpredictable.

Results

Responses to T1. The mean proportion of correct responses to T1 at the short SOA and long SOA was .75 and .76, respectively. These values did not differ significantly, $F(1,\ 15) = 0.25$, $p > .6$.

Responses to T2. The mean proportion of correct responses to T2, as a function of SOA, and as a function of the task performed on T1 is reported in Figure 1 (lower-left panel). An ANOVA performed on the mean proportion of correct responses to T2 revealed a significant effect of SOA, $F(1,\ 15) = 240.8$, $p < .001$, a significant effect of the T1 task, $F(1,\ 15) = 22.8$, $p < .001$, and a significant interaction between SOA and T1 task, $F(1,\ 15) = 5.3$, $p < .03$. The SOA effect was also significant when the results from the ignore-T1 condition were analysed separately, $F(1,\ 15) = 98.1$, $p < .001$. The ANOVA carried out on d' revealed the same pattern of results: There was a significant effect of SOA, $F(1,\ 15) = 143.2$, $p < .001$, a significant, effect of

T1 task, $F(1, 15) = 46.4$, $p < .003$, and a significant interaction between these two variables, $F(1, 15) = 8.1$, $p < .02$. The SOA effect was also significant when the results from the ignore-T1 condition were analysed separately, $F(1, 15) = 70.5$, $p < .001$.

Rate of stimulation. The mean blank interval durations in the ignore-T1 and report-T1 conditions were 75 ms and 81 ms, respectively. These values did not differ significantly, $F(1, 15) = 2.1$, $p > .2$.

Discussion

Despite the difference in the pattern of stimulation that we introduced between T1 and T2, T1 was evidently still difficult to ignore. Indeed, the size of the SOA effect for the ignore-T1 condition was about the same in Experiment 3 (.15) as it was in Experiments 1 and 2 (mean of .14 across the two experiments). Thus, our expectation that this difference would help participants to ignore T1 was not supported by the results.

Nonetheless, the results of Experiment 3 provided a further demonstration of a tactile AB in a form very similar to that put in evidence in the previous experiments. The ability to report which finger was stimulated first on the second hand to be stimulated declined as the SOA between hands was reduced, and this decrease was larger when a report had to be made for both hands than when the first stimulated hand could be ignored.

EXPERIMENT 4

In Experiment 3, we again found the participants found it difficult to ignore an irrelevant tactile stimulus, even when that stimulus had a different temporal structure from the one to be reported. However, as in Experiment 1, the order of stimulation of the hands was unpredictable. Perhaps this uncertainty about hand order made it difficult to use the difference in temporal patterning between T1 and T2 to construct an effective filter to exclude T1.

In Experiment 4 we provided two different cues to help participants to distinguish T1 from T2, and thereby ignore T1 when it was desirable to do so (in ignore-T1 trial blocks). Although each cue, by itself, was shown to be ineffective in allowing participants to ignore T1 (in Experiments 2 and 3), it is possible that combining the cues would allow participants to achieve something they could not achieve with either cue in isolation. In Experiment 4, we used the same difference in temporal patterning between T1 and T2 when T1 was to be ignored, providing one cue to distinguish T2 from T1;

and we made the order of stimulation of the hands predictable, providing another cue based on spatial differences between T2 and T1.

By providing both cues simultaneously we tested the hypothesis that participants would be able to combine selection cues to construct a more effective filter than they could with each cue in isolation. Perhaps a form of early selection filtering could be adopted, based on hand of stimulation, as well as a form of late-selection filtering, based on differences in T1 and T2 temporal patterning.

Method

Stimuli and apparatus. The same tactile stimuli as those used in Experiment 3 were used in Experiment 4. That is, in the report-T1 blocks of trials of Experiment 4, both T1 and T2 were sequential triplets of brief presses. As in Experiment 3, T1 in the ignore-T1 trial blocks was composed of a single 20 ms press applied simultaneously to the middle and index fingers of the same hand.

Design and procedure. The design and procedure were the same as in Experiment 3 except that which hand was stimulated first was the same on all trials for any given participant. For half of the participants, the order of stimulation was left–right; for the other half the order was right–left.

Results

Responses to T1. The mean proportion of correct responses to T1 at the short SOA and long SOA was .80 and .79, respectively. These values did not differ significantly, $F(1, 15) = 0.52$, $p > .4$.

Responses to T2. The mean proportion of correct responses to T2, as a function of SOA, and as a function of the task performed on T1 is reported in Figure 1 (lower-right panel). An ANOVA performed on the mean proportion of correct responses to T2 revealed a significant effect of SOA, $F(1, 15) = 148.4$, $p < .001$, a significant effect of the T1 task, $F(1, 15) = 149.8$, $p < .001$, and a significant interaction between these two variables, $F(1, 15) = 39.1$, $p < .001$. The SOA effect was not significant when the results from the ignore-T1 condition were analysed separately ($F < 1$). The ANOVA carried out on d' values revealed the same pattern of results: There was a significant effect of SOA, $F(1, 15) = 55.4$, $p < .001$, a significant effect of the T1 task, $F(1, 15) = 101.0$, $p < .001$, and a significant interaction between these two variables, $F(1, 15) = 17.9$, $p < .001$. The SOA effect on d' values was not significant when the results from the ignore-T1 condition were analysed separately ($F < 1$).

Rate of stimulation. The mean blank interval durations in the ignore-T1 and report-T1 conditions were 73 ms and 85 ms, respectively. This 12 ms difference resulted in a significant effect of T1 task on blank duration, $F(1, 15) = 4.5$, $p < .05$.

Joint analysis of Experiments 1–4

The most informative results from all the present experiments (i.e., T2 report accuracy and d' values) were analysed as a function of hand order of presentation of T1 and T2 (unpredictable: Experiments 1 and 3 vs. predictable: Experiments 2 and 4), T1-T2 similarity (similar: Experiments 1 and 2 vs. dissimilar: Experiments 3 and 4), SOA, and the type of task on T1. In the present ANOVA, hand-order and T1–T2 similarity were considered as between-subject variables, whereas SOA and T1 task were considered as within-subject variables. Only the results from trials with a correct response to T1 were included in the analysis.

As one would expect, all the effects that were significant in the analyses of the individual experiments were now even more so. The critical test we were looking were those involving the factors involving the different experiments. Most importantly, the four-way interaction (predictability of hand, similarity of T1 stimulation, SOA, and report vs. ignore T1) approached significance, $F(1, 60) = 3.0$, $p < .09$. In addition, three-way interactions between hand-order, T1–T2 similarity, and SOA, $F(1, 60) = 11.1$, $p < .002$, and between hand-order, SOA, and task on T1, $F(1, 60) = 8.2$, $p < .006$, were also significant. Similar results were obtained in the ANOVA performed on mean d' values. The four-way interaction between all factors approached significance, $F(1, 60) = 3.1$, $p < .08$. The three-way interactions between hand-order, T1–T2 similarity, and SOA, $F(1, 60) = 12.7$, $p < .001$, and between hand-order, SOA, and task on T1, $F(1, 60) = 4.2$, $p < .04$, were also significant.

In order to obviate to the apparent lack of power to detect the four-way interaction and is suggested by the patterns of results displayed in Figure 1, the results from report-T1 trials and ignore-T1 trials were considered separately in two subanalyses. An ANOVA carried out on the mean percentage correct localisation responses to T2 in trials in which T1 had to be reported indicated only the main effect of SOA, $F(1, 60) = 426.3$, $p < .001$, $F < 1$, for all other main effects or interactions. The only significant factor in the ANOVA carried out on d' values for the same type of trials was also SOA, $F(1, 60) = 298.2$, $p < .001$, $F < 1$, for all other main effects or interactions.

An ANOVA carried out on the mean percent of correct localisation responses to T2 in trials in which T1 could be ignored indicated the main effects of hand-order, $F(1, 60) = 6.8$, $p < .02$, and SOA, $F(1, 60) = 131.0$, $p <$

.001. The two-way interaction between hand-order and SOA, $F(1, 60) = 26.7$, $p < .001$, and the three-way interaction between hand-order, SOA, and T1–T2 similarity, $F(1, 60) = 14.2$, $p < .001$, were significant. Analogous results were obtained in the ANOVA carried out on d' values estimated on the basis of the same type of trials. There were main effects of hand-order, $F(1, 60) = 7.3$, $p < .01$, and SOA, $F(1, 60) = 99.2$, $p < .001$. The two-way interaction between hand-order and SOA, $F(1, 60) = 19.4$, $p < .001$, and the three-way interaction between hand-order, SOA, and T1–T2 similarity, $F(1, 60) = 16.2$, $p < .001$, were significant.

Discussion

In Experiment 4, accuracy of report of T2 decreased sharply as SOA was reduced for report-T1 trials, but in sharp contrast there was no effect of SOA for ignore-T1 trials. This pattern of results shows that it is possible, under appropriate conditions, to ignore a tactile distractor presented just before a tactile target. This finding argues against a purely automatic form of attentional capture in taction. The absence of an SOA effect for ignore-T1 trials was also in sharp contrast with what was found in Experiments 1, 2, and 3. Evidently, combining a predictable order of hand stimulation and a tactile pattern difference between T1 and T2 allowed participants to ignore T1 during ignore blocks. Not surprisingly, because the report-T1 conditions were identical in all four experiments, there was no difference in the magnitude of the SOA effect on accuracy of report of T2 for the report-T1 trial blocks across the four experiments. The results for these equivalent conditions displayed a remarkable stability across experiments, boosting our confidence in the differences we found for the conditions that did differ across experiments, that is, in the ignore-T1 conditions.

GENERAL DISCUSSION

The results from Experiments 1–4 provide clear-cut and unambiguous demonstrations of an AB effect produced entirely with tactile stimulation. In these experiments the accuracy of report of an attribute of a second tactile target decreased more as the SOA between the first target (T1) and the second target (T2) was reduced when an attribute of T1 also had to be reported relative to the decrease observed when T1 could be ignored. This AB effect was obtained under conditions in which the same task and selection criteria were in effect for T1 and T2, ensuring that task switching, and/or switching of selection criteria for T1 and T2, could not provide an explanation for the greater effects of SOA in the report-T1 condition than in the ignore-T1 condition.

These results are important because they suggest that the underlying causes of the AB effect are likely to be general in the sense that they appear to operate in a similar fashion following visual input (e.g., Raymond, Shapiro, & Arnell, 1992), auditory input (Arnell & Jolicœur, 1999; Soto-Faraco & Spence, 2002), and tactile input (as demonstrated herein; see also Hillstrom, Shapiro, & Spence, 2002). In every case, processing a first target for the purpose of the later report of one of its attributes causes a deficit in the ability to report an attribute of a second target presented at a short SOA relative to the first target. This generality across different input modalities suggests that there is either a single general mechanism that is shared by all studied modalities, or that there are similar within-modality mechanisms that are repeated within each studied modality. The fact that there have been multiple demonstrations of crossmodal AB effects (e.g., Arnell & Jolicœur, 1999; Arnell & Larson, 2002; Dell'Acqua, Jolicœur et al., 2003; Dell'Acqua, Turatto, & Jolicœur, 2001; Jolicœur, 1999b; Soto-Faraco et al., 2002) implies that one or more common supramodal mechanism or resource must sometimes be involved in processing inputs from different sensory modalities.

Having ruled out masking of T2 by T1 presentation as a possible cause of the deficits evidenced in Experiments 1–4, one may wonder whether such deficits reflect a true AB deficit (i.e., a T2 consolidation difficulty), or instead a different form of deficit, perhaps induced by having to attend to spatially different locations. In this alternative perspective, it was a general difficulty to move attention from one hand to the other hand that caused the AB-like pattern of results found in the present study. The assumption in this case would be that participants, on encode-T1 trials, took longer to process T1 compared to the ignore-T1 condition and that resulted in an increased probability to miss T2 when T1 and T2 were presented in close temporal contiguity. This argument is obviously plausible, but it encounters one major objection. Attention can demonstrably be split between opposite fingers of both hands. Craig (1985, Exps. 4–5) compared the ability of participants to integrate and discriminate tactile patterns presented to either two fingers of the same hand (ipsilateral condition), or to opposite fingers of the different hands (bilateral condition). The to-be-processed tactile patterns were displayed at SOAs varying from 0 ms to 400 ms, and participants were either warned in advance about the location of presentation of the stimuli, or they received no information about it. Interestingly, although a clear reduction in detection and integration accuracy was observed in the ipsilateral condition, an optimal performance was observed at all SOAs in the bilateral condition, even when participants did not know in advance the order of stimuli presentation. These results, in Craig's (1985) view, implied that participants were able to split their attention almost perfectly between the fingerpads of the two hands (see also Craig, 1989). In our view, these results have also implications for the interpretation of the present findings, in that they suggest that the AB observed in Experiments 1–4 was an encoding deficit at all effects, namely, T2 was missed not because the hand through T2 was delivered was momentarily unattended, but because, as proposed for other within-modality architecture of the AB effect, T2 location consolidation was momentarily postponed at the shorter SOA.

Despite strong evidence for crossmodal interactions mediated by a supramodal representation of space (Eimer & van Velzen, 2002), and involuntary shifts of attention sometimes caused by sudden onsets in a different sensory modality (Turatto, Galfano, Bridgeman, & Umiltà, 2004; see also Turatto, Benso, Galfano, & Umiltà, 2002), the exact conditions that lead to crossmodal AB effects remain elusive (Arnell & Larson, 2002; Chun, & Potter, 2001; Duncan, Martens, & Ward, 1997; Potter et al., 1998; Soto-Faraco et al., 2002). One candidate capacity-demanding process that has been proposed as a likely common underlying cause of the AB, whether it be within each modality, or a shared supramodal mechanism, is the short-term consolidation of information in STM (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998). The present results provide additional converging evidence for this possibility.

Although certain stimuli sometimes appear to attract attention involuntarily (particularly sudden onsets), there is good evidence that the degree to which stimuli attract attention—even for sudden onsets—is controlled by an interaction between aspects of the stimulus and the current intentions and goals of the observer. Work by Folk and his colleagues demonstrates nicely that attentional capture can be modulated by top-down attentional set (Folk & Remington, 1998; Folk et al., 1992; Folk, Remington, & Wright, 1994). The AB paradigm highlights some aspects of attentional control, indeed, depends on this top-down control because the control condition (i.e., the baseline against which results from the experimental condition are compared) often requires that a salient stimulus be ignored. For example, a control condition often used in the AB paradigm is to present a distinctive target, as T1, such as a white letter presented in an RSVP stream of grey letters, and to require report only of T2. When T1 and T2 are presented at the same physical location, observers are usually able to process T2 apparently without any cost associated with the mere presentation of a salient T1 (e.g., Raymond et al., 1992). The AB effect is found, in contrast, when the observer must report aspects of both T1 and T2. The ability to ignore irrelevant salient stimuli in the AB paradigm has also been demonstrated for crossmodal situations. For example, Jolicœur (1999b), Exp. 1) found no evidence for a deficit in the processing of a visual T2 following the presentation of a tone for which no response was required. Folk, Leber, and Egeth (2002) examined contingent capture in the context of visual targets presented using RSVP. The distractors were presented at a different spatial location (above, below, left, or right of the central RSVP stream). Attentional capture was revealed by a loss of accuracy in the report of the target letter. When targets were selected based on search for a specific colour (e.g., report the red letter presented among letters of other colours), peripheral distractors that matched the target colour (e.g., red) captured attention, but peripheral distractors in other colours did not. The results demonstrate that observers in the experiments of Folk et al. were not able to implement an effective conjunctive input filter to constrain input of a specific feature at a single spatial location.

Isolating the precise conditions under which sensory signals capture attention is a complex theoretical challenge. The present findings provide interesting new insights into this problem in the context of tactile stimulation. In Experiments 1, 2, and 3, observers were less accurate in their reports of the T2 tactile stimulus when T2 followed T1 at short SOA, relative to the long SOA condition even when they were instructed to ignore T1. These results provide evidence of involuntary attentional capture by T1. Interestingly, capture was modulated by an interaction between the predictability of the order of stimulation of the hands and the similarity in the patterns of tactile stimulation between T1 and T2, providing evidence for the importance of top-down attentional control settings, as found in the visual domain by Folk and his colleagues. Strong evidence for capture was found except when order of stimulation was predictable (fixed within blocks) and when T1 and T2 were dissimilar. Each one of these two factors alone (predictability of order of stimulation, similarity of T1 and T2) was insufficient to prevent capture (Experiments 1, 2, and 3). As in the visual domain, it appears that observers have difficulty in implementing a conjunctive input filter to select a particular type of tactile input only from one location. Indeed, there were no significant differences in the magnitude of the SOA effect in the control condition (T2 only) across Experiments 1, 2, and 3. As in vision, however, when the feature defining T2 for selection was sufficiently different from the features present in T1, participants were able implement an effective input filter (Experiment 4). It is possible that larger differences in patterns of tactile stimulation could, by themselves, cause a release from capture, even under conditions of location uncertainty, and this would likely be a fruitful avenue for future research. More generally, modulations of attentional capture could be used as a paradigm to map out the functional dimensions of tactile stimulation.

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