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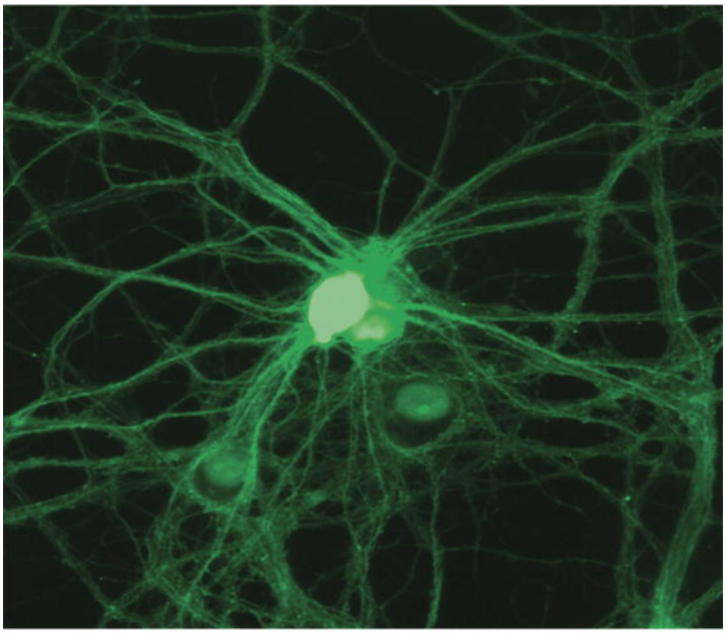

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Research Report

Short term memory for tactile stimuli

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ABSTRACT

Research has shown that unreported information stored in rapidly decaying visual representations may be accessed more accurately using partial report than using full report procedures (e.g., [Sperling, G., 1960. The information available in brief visual presentations. Psychological Monographs, 74, 1–29.]). In the 3 experiments reported here, we investigated whether unreported information regarding the actual number of tactile stimuli presented in parallel across the body surface can be accessed using a partial report procedure. In Experiment 1, participants had to report the total number of stimuli in a tactile display composed of up to 6 stimuli presented across their body (numerosity task), or else to detect whether or not a tactile stimulus had previously been presented in a position indicated by a visual probe given at a variable delay after offset of a tactile display (i.e., partial report). The results showed that participants correctly reported up to 3 stimuli in the numerosity judgment task, but their performance was significantly better than chance when up to 5 stimuli were presented in the partial report task. This result shows that short-lasting tactile representations can be accessed using partial report procedures similar to those used previously in visual studies. Experiment 2 showed that the duration of these representations (or the time available to consciously access them) depends on the number of stimuli presented in the display (the greater the number of stimuli that are presented, the faster their representation decays). Finally, the results of a third experiment showed that the differences in performance between the numerosity judgment and partial report tasks could not be explained solely in terms of any difference in task difficulty.

1. Introduction

Recent studies have demonstrated that people are generally quite poor at reporting the number of vibrotactile stimuli presented in parallel over their body surface (Gallace et al., 2006b; see also Gallace et al., 2007a,b, in press). In particular, the percentage of errors in counting the number of bodily locations stimulated at any one time becomes very high (i.e., >30% errors) when as few as 3 vibrotactile stimuli are presented (see also Alluisi et al., 1965; Geldard and Sherrick, 1965; cf. Riggs et al., 2006). Other studies have reported that the phenomenon of "change blindness" (i.e., the inability of people to detect changes in consecutively presented visual scenes; e.g., Rensink, 2002; Simons and Rensink, 2005; see also Rensink, 2004) also affects the perception of tactile stimuli (e.g., Gallace et al., 2005, 2006a,c). These two sets of findings

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therefore suggest a fundamental limitation in the number of tactile items that can be monitored or explicitly accessed at any one time (e.g., Cowan, 2001; Gallace et al., 2006a; Levin and Varakin, 2004; see also Gallace and Spence, 2007).

It is, however, important to note that the limitations on tactile information-processing capacity may not be the same as the limitations on conscious tactile perception. In fact, several studies have previously shown that the representation of a stimulus can be processed in the cognitive system without it necessarily being consciously perceived or reported (e.g., Köhler and Moscovitch, 1997; see also Gallace and Spence, 2007). In particular, research has demonstrated that representations of undetected visual changes can still affect participants' responses (e.g., Fernandez-Duque and Thornton, 2003; Thornton and Fernandez-Duque, 2000; cf. Rensink, 2004). For instance, Thornton and Fernandez-Duque (2000) reported that even when participants were unaware of a change in the orientation of an item between two consecutively presented visual displays, the undetected new orientation of that object biased participants' responses in a subsequent discrimination task.

The rapid temporal decay of stimulus information may explain this difference between information processing and phenomenal consciousness. Information that is processed rapidly and transiently may have decayed before the slow processes associated with conscious perception can operate (see Libet et al., 1967; cf. Libet, 1967). Many years ago, Sperling (1960) demonstrated that participants who were instructed to remember all of the alphanumerical characters presented in a visual matrix for 500 ms were able to report an average of about 4 or 5 items. However, when partial report was required instead (by presenting a post-display acoustic probe that indicated which particular row of the matrix the participants should report), the estimated storage capacity of the visual array rose to 12–18 items. Such a result has been taken to demonstrate the existence of a specific representation (i.e., iconic memory; see Coltheart, 1980, 1983; Di Lollo, 1977; Neisser, 1967) of high capacity (but not necessarily entering awareness) and subject to very rapid decay (for a review, see Coltheart, 1980). A similar short-term form of memory has also been reported in the auditory modality (Darwin et al., 1972). It is, however, worth noting here that the advantage of the partial as compared with the full report procedure reported by Darwin and his colleagues (1972) when using auditory stimuli was much smaller than that reported previously in the visual modality (i.e., the capacity of auditory sensory memory was estimated at about 5 items).

Only one study has tried to investigate the accessibility of short-term representations of tactile stimuli presented simultaneously on the fingertips of both hands (Bliss et al., 1966). Specifically, Bliss et al. (1966) delivered up to twelve stimuli to the twenty-four inter-joint segments of participants' fingers (excluding the thumbs). The participants had to report the digit segments stimulated after each stimulus presentation using an alphabetical labelling system. Bliss et al. found that when the participants had to report the stimuli presented to all eight fingers (whole report procedure), the maximum number of stimuli that participants could correctly report averaged about 3.6 (out of a maximum of 12 possible correct). However, when a partial report procedure was used instead (involving the post-stimulus cuing of individual fingers; equivalent to the partial report procedure used by Sperling, 1960, in his studies of visual memory), the participants were able to report one more location successfully (i.e., 4.6 correct; corresponding to a 27% improvement in performance) as compared to the whole report procedure. Although significant, this represents a very modest improvement in performance relative to that seen in vision (although similar to that reported in audition; see Darwin et al., 1972), where up to 12–14 letters more than the number of stimuli reported using the whole report procedure are available to participants when the partial report procedure is used; i.e., corresponding to a 180% improvement in performance. Bliss et al. argued that their results provided evidence for a "sensory" form of short-term representation for tactile stimuli that had a large capacity but short duration (i.e., which suffered from rapid decay), equivalent to the iconic memory investigated in the visual modality (e.g., Coltheart, 1980; Sperling, 1960; for attempts to investigate other forms of tactile memory, see Heller, 1987; Mahrer and Miles, 1999, 2002; Miles and Borthwick, 1996).

One reason for the small size of the tactile partial report effect, relative to the visual effect, may be the method of response labelling used by Bliss et al. (1966) in their study. In particular, they asked participants to associate each digit segment with a letter of the alphabet. This rather complex response procedure may itself have consumed considerable cognitive resources, which could have impaired the memory capacity of the participants in the subsequent report of the tactile stimuli presented (e.g., Dalton et al., submitted for publication; de Fockert et al., 2001; Lavie, 2005; Lavie and de Fockert, in press).

In addition, the level of stimulus processing in Bliss et al.'s (1966) study might have differed from that required in the classical partial report task. Specifically, after having learned the correspondences between alphabetical labels and finger sectors, the full report task used by Bliss et al. only required the "detection" of the stimuli presented, whereas the partial report procedure further required the correct "identification" of the stimuli that had been presented, which presumably involves further perceptual processing. One might therefore expect greater differences between the full and partial report procedures in identification than in detection tasks.

No published study has as yet attempted to investigate the short-term representations of tactile stimuli distributed across the body surface, rather than on the fingertips (for an early study in which participants had to point to the position of tactile stimuli presented on their forearm after a variable interval delay, see Gilson and Baddeley, 1969; for a more recent replication of Gilson and Baddeley's study, see also Miles and Borthwick, 1996). Differences in the duration and/or capacity of short-term representations of stimuli presented on the fingertips versus on the rest of the body surface might be expected given that a relatively larger proportion of the somatosensory cortex is given over to the representation of the hands than to other parts of the body (e.g., Nakamura et al., 1998; Narici et al., 1991; Penfield and Rasmussen, 1950). That is, the relative extension of the neural representations across the somatosensory cortex might constrain the duration, the capacity, and/or the access to tactile information presented to different parts of the body surface. The fact that tactile short-term memories appear to be organized somatotopically, along the lines of the representation in SI (Harris et al., 2001), underlines the possible role of cortical representation in short-term representation of tactile stimuli.

Finally, it is worth noting here that whereas the position of the stimuli presented on the fingertips might be more easily coded in terms of verbal categories (the thumbs, the index finger, the middle finger, etc.), the location of the stimuli across the body surface is more likely to be coded in terms of their spatial location on a continuous receptor surface (at least under conditions in which "anchor" body locations, such as wrist, knee, or elbow, are not used; cf. Cholewiak and Collins, 2003; Cholewiak et al., 2004; see Gallace and Spence, 2007). In line with this suggestion, one might expect possible important differences in tactile STM for stimuli presented on the body as compared to stimuli presented on the fingertips.

1.1. *Experiment 1*

In Experiment 1, we investigated whether information regarding the number of vibrotactile stimuli presented across the body might remain accessible for a brief period of time after stimulation, despite being unavailable to conventional verbal report. In particular, we thought it possible that the identification of a specific designated position on the body by an appropriate post-stimulus probe may allow a tactile stimulus that had been previously presented at that location to be described, even when a full report of the total number of stimuli presented would appear to suggest that such a description is not possible. In Experiment 1, the participants had to report the number of vibrotactile stimuli (1–6) presented across the body surface in each trial (cf. Gallace et al., 2006b). In a second block of trials, the participants had to report whether or not a vibrotactile stimulus (part of a display composed of up to 6 stimuli) had been previously presented on the body position indicated by a post-stimulus visual probe.

We predicted that the presentation of the post-stimulus visual probe should facilitate correct identification of the previously presented tactile stimulus at the probe location. This tactile analogue of the phenomenon of partial report should be found even when information about the tactile stimulus is not accessed by conventional judgment tasks such as numerosity estimation. That is, the amount of information contained in the representation of the tactile stimuli presented across the body is higher than the information that can be reported correctly (i.e., Sperling, 1960). Moreover, by analogy with the concept of visual iconic memory, it should be expected that the longer the interval between the presentation of the tactile display and the probe stimulus, the worse the performance of participants in the tactile partial report task.

1.2. *Experiment 2*

In order to test whether the duration and the capacity of the short-term representations of tactile stimuli are mutually related, we increased the length of the temporal delay between the presentation of the tactile stimuli and the visual probe in Experiment 2. If the duration of tactile short-term representations is affected by the amount of tactile information presented/stored in the display, then we should expect that the SOAs at which the post-stimulus probe ceases to be effective in improving participants' performance would decrease as the number of tactile stimuli presented increases.

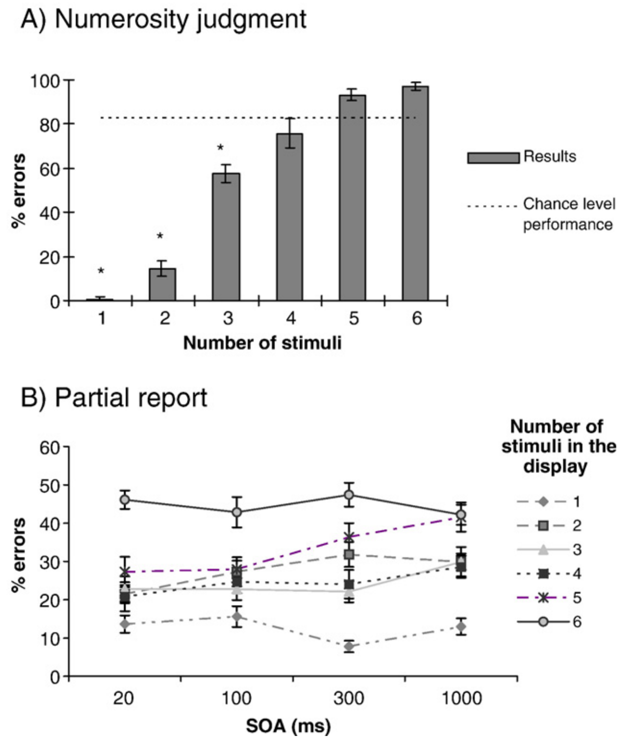

Fig. 1 – Results of Experiment 1: (A) Mean error rates in the numerosity block of trials as a function of the number of tactors activated. Chance level performance is represented by the dotted line. Asterisks highlight those values that were significantly different from chance; (B) mean error rates in the partial report block of trials as a function of the number of tactors activated and of the SOA between the tactile display and the visual probe. Error bars represent the standard errors of the means.

It is worth noting here that in Experiment 1, we presented the partial report block after the numerosity judgment block. Similarly, Sperling (1960) always presented the full report task before the partial report task. However, one might wonder whether partial report performance may be better than numerosity performance simply because of perceptual learning. Therefore, in Experiment 2, we presented the partial report block before the numerosity judgment task to investigate this possible confound.

1.3. *Experiment 3*

Given that a numerosity judgments task was used in Experiments 1 and 2, one might argue that this task does not actually correspond to a full report of the stimuli that have been presented. In particular, the judgment of numerosity only requires a person to represent the occurrence of a stimulus, whereas full report requires the representation of all the attributes of each individual stimulus (e.g., typically letter identity in the visual case). Moreover, tactile numerosity judgments are known to be particularly difficult (e.g., Gallace et al., 2006b). These differences might eventually lead to a discrepancy between the results of our experiments and previous studies of short-term visual representations. In order to try and eliminate this possibility in Experiment 3, we compared participants' performance in a numerosity judgment task (similar to that used in Experiments 1 and 2) to their performance in a task in which they had to report the positions of all the stimuli presented rather than their number (i.e., using a procedure more similar to the full report used by Sperling, 1960).

2. Results

2.1. *Experiment 1*

Trials in which the participants failed to give a response before the trial was terminated (less than 1% of trials overall) were not analysed. The results obtained in the numerosity judgment block of trials of Experiment 1 are shown in Panel A of Fig. 1 . This graph shows that the number of errors made by participants when between 2 and 5 stimuli were presented increases with the number of stimuli presented in the display. The mean percentages of errors in the numerosity judgment block were submitted to a repeated measures analysis of variance (ANOVA) with the factor of numerosity (6 levels). This analysis resulted in a significant main effect [$F(5,50)=134.9$; $p<0.0001$], with the number of errors increasing as the number of stimuli composing the display increased. This result is consistent with the extant literature on tactile numerosity judgments (see Gallace et al., 2006b, 2007a). An LSD post hoc test on the main effect showed significant differences between each pair of consecutive numbers (all $p<0.05$), except for the comparison between 5 and 6 stimuli ($p=0.44$). For each numerosity, the mean percentage of errors was then compared with chance level performance by means of planned *t*-tests (i.e., 83.3% errors; note that with 6 responses available to the participants, the probability of responding correctly by chance equals 100/6=16.6%). This analysis revealed that performance was significantly better than chance for displays composed of 1, 2, and 3 stimuli (all $p<0.001$) but not for displays composed of 4, 5, and 6 stimuli. That is, participants' tactile numerosity judgments were no better than chance for arrays consisting of 4 or more stimuli. It is worth mentioning here that all of the participants' errors were underestimations of the number of stimuli presented, analogous to what has been previously reported in studies that have adopted a similar task (e.g., Gallace et al., 2006b, 2007a).

The results of the partial report task of Experiment 1 are shown in panel B of Fig. 1. This graph shows that the shorter the SOA between the tactile display and the probe, the better was participants' performance. The mean percentage of errors in the partial report block was submitted to a repeated measures ANOVA with the factors of Numerosity (6 levels) and SOA (4 levels). This analysis revealed a significant main effect of numerosity [$F(5,50)=42.85$; $p<0.0001$] and of SOA [$F(3,30)=5.45$; $p<0.001$], and a significant interaction between these two factors [$F(15,150)=1.97$; $p<0.05$]. The main effect of SOA was then analysed with 6 separate ANOVAs, one for each

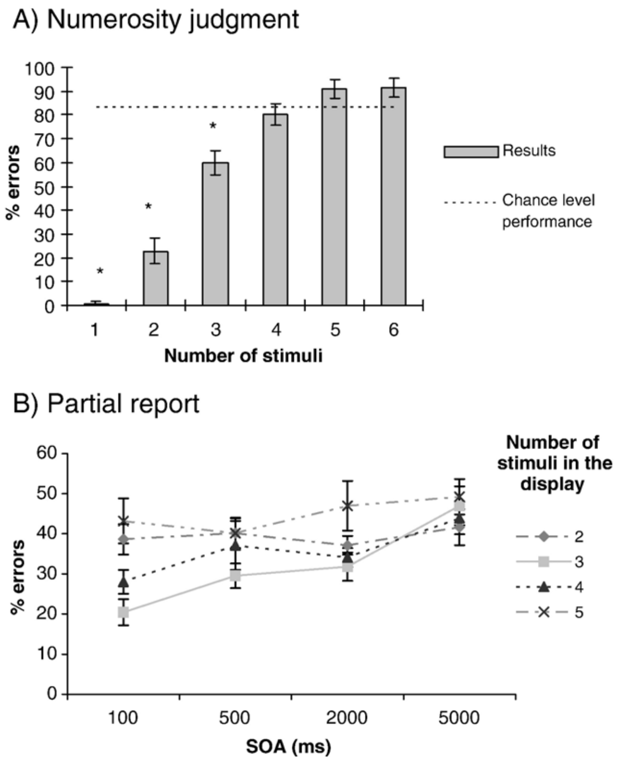

Fig. 2 – Results of Experiment 2: (A) Mean error rates in the numerosity block of trials as a function of the number of tactors activated. Chance level performance is represented by the dotted line. Asterisks highlight those values that were significantly different from chance; (B) mean error rates in the partial report block of trials as a function of the number of tactors activated and of the SOA between the tactile display and the visual probe. Error bars represent the standard errors of the means.

level of the numerosity factor. These analyses revealed a significant effect of SOA for displays composed of 1, 2, and 5 stimuli [$F(3,30)=3.85$, $p<0.05$; $F(3,30)=3.31$, $p<0.05$; $F(3,30)=4.85$, $p<0.05$, respectively], but not for displays composed of 3, 4, and 6 stimuli [$F(3,30)=2.95$; $F(3,30)=2.29$; $F(3,30)<1$, respectively, all *n.s.*]. An LSD post hoc test on the effect of SOA for 1 stimulus presented in the display revealed significant differences between 20 and 300 ms ($p=0.02$) and between the 300- and the 100-ms SOAs ($p=0.03$). The LSD post hoc test on the effect of SOA for displays composed of 2 stimuli revealed significant differences between 20 and 300 ms ($p=0.005$) and between 20 and 1000 ms SOAs ($p=0.02$). The LSD post hoc test on the effect of SOA for displays composed of 5 stimuli revealed significant differences between 20 and 300 ms ($p=0.04$), between 20 and 1000 ms ($p=0.003$), and between the 100- and the 1000-ms SOAs ($p=0.004$). These results show that when either 2 or 5 stimuli were presented in the display, the shorter the SOA between the tactile display and the probe, the better was participants' performance (see Fig. 1B). Note that when only a single stimulus was presented in the display, the effect of SOA was not in the expected direction. That is, the best performance was obtained with an intermediate SOA (i.e., 300 ms) rather than with shorter SOAs. It is, however, worth considering here that when only a single stimulus was presented in the display, its location might have been coded in terms of a semantic labels rather than in terms of the stimulus's spatial or somatotopic attributes. The fact that a certain amount of time is required to gain access to the semantic code associated with the stimulated location might perhaps help to explain why better performance was not reported for the shorter SOAs under this condition of stimulus presentation.

In order to ascertain whether the number of errors increased linearly with SOA, we performed regression analyses for each number of stimuli presented in the display. None of these analyses were significant, although a trend toward significance was reported for displays composed of 3, 4, and 5 stimuli [r^2=88, p=0.06; r^2=81, p=0.09; r^2=85, p=0.07, respectively]. For all three of these conditions, the number of errors increased linearly with increasing SOA.

For each SOA, and for each numerosity, the mean percentage of errors was then compared with chance level performance (i.e., 50% errors) using planned *t*-tests. This analysis revealed significant differences from chance for displays composed of 1–4 stimuli at each SOA (all $p<0.001$). For displays composed of 5 stimuli, the percentage of errors was significantly different from chance at each SOA, but only at a borderline-significant level for the 1000-ms SOA ($p=0.053$). For displays composed of 6 stimuli, the percentage of errors was significantly different from chance only for the 1000-ms SOA ($p<0.05$).

2.2. Experiment 2

Trials in which the participants failed to give a response before the trial was terminated (less than 1% of trials overall) were not analysed. The results obtained in the numerosity judgment block of trials of Experiment 2 are shown in Panel A of Fig. 2. This graph shows that the number of participants' errors increased with the number of stimuli presented in the display. The mean percentage of errors in the numerosity judgment block was submitted to a repeated measures ANOVA with the factors of numerosity (6 levels). This analysis resulted in a significant main effect of numerosity [$F(5,50)=87$, $p<0.0001$], with the number of errors increasing as the number of stimuli composing the display increased (see Fig. 2A). This result is consistent with the results of Experiment 1 and with those previously reported in the literature regarding tactile numerosity judgments (see Gallace et al., 2006b, 2007a). A post hoc LSD test on the main effect revealed significant differences between each pair of consecutive numerosities (all $p<0.05$), except for the comparison between 5 and 6 stimuli ($p=0.89$). The difference between displays composed of 4 and 5 stimuli showed a trends toward significance ($p=0.07$).

For each numerosity value, the mean percentage of errors was then compared with chance level performance (i.e., 83.6% errors) using planned *t*-tests. This revealed significant differences for displays composed of 1–3 stimuli (all $p<0.001$), but not for displays composed of 4 or more stimuli, just as in Experiment 1.

The results of the partial report task of Experiment 2 are shown in panel B of Fig. 2. This graph shows that the shorter the SOA between the tactile display and the probe, the better was participants' performance. The mean percentage of errors in the partial report trials was submitted to a repeated measures ANOVA with the factors of numerosity (4 levels) and SOA (4 levels). This analysis revealed a significant main effect of numerosity [$F(3,30)=10.18$; $p<0.0001$] and of SOA [$F(3,30)=7.63$; $p<001$] and a borderline-significant interaction between these two factors [$F(12,90)=1.85$; $p=0.07$]. The main effect of SOA was then analysed with 4 separate ANOVAs, one for each level of the numerosity factor. This analysis revealed a significant main effect of SOA for displays composed of 3 or 4 stimuli [$F(3,30)=10.86$; $p<0.0001$; $F(3,30)=3.2$; $p<0.05$, respectively], but not for displays composed of either 2 or 5 stimuli [all $F(3,30)<1$; *n.s.*]. An LSD post hoc test on the effect of SOA when 3 stimuli were presented in the display revealed a borderline-significant difference between 100 and 500 ms ($p=0.06$) and significant differences between 100 and 2000 ms ($p=0.02$), between 100 and 5000 ms ($p=0.0001$), between 500 and 500 ms ($p=0.0008$), and between 2000 and 5000 ms ($p=0.003$). In all of these conditions, the shorter the SOA, the better the participants' performance. An LSD post hoc test on the effect of SOA for displays composed of 4 stimuli revealed a significant difference between 100 and 5000 ms ($p=0.004$) and borderline-significant differences between 100 and 500 ms ($p=0.09$) and between 1000 and 5000 ms ($p=0.06$). Once again, the shorter the SOA, the better the participants' performance (see Fig. 2B). In order to ascertain whether the number of errors increased linearly with SOA, we performed regression analyses for each number of stimuli presented in the display. These analyses failed to reveal significant effects (all *ps n.s.*).

Table 1 – Analysis of the differences between chance level performance and number of errors actually made by participants in the partial report block of trials of Experiment 2 for each number of stimuli composing the displays and for each SOA

Number of stimuli	2	3	4	5
SOA				
100 ms	$p<0.05$	$p<0.05$	$p<0.05$	*n.s.*
500 ms	$p<0.05$	$p<0.05$	$p<0.05$	$p<0.05$
2000 ms	$p<0.05$	$p<0.05$	$p<0.05$	*n.s.*
5000 ms	$p=0.08$	*n.s.*	n.s.	n.s.

For each SOA, and for each numerosity value, the mean percentage of errors was compared with chance level performance (i.e., 50% of errors) using *t*-tests (see Table 1). These analyses revealed the following: significant differences when the display was composed of 2 stimuli for each SOA (all $p<0.05$), except 5000 ms where a borderline-significant effect was reported ($p=0.08$); significant differences for displays composed of 3 stimuli for all SOAs (all $p<0.05$), except 5000 ms SOA (*n.s.*); significant differences when 4 stimuli composed the display for all SOAs (all $p<0.05$), except 5000 ms (*n.s.*); and significant differences when 5 stimuli composed the display at the 500-ms SOA, but not any of the other SOAs (all *n.s.*).

In order to verify whether the order in which the two experimental conditions (full and partial report) were presented in Experiments 1 and 2 affected participants' performance (note that that the numerosity block of trials preceded the full report block of trials in Experiment 1 and followed the full report condition in Experiment 2), we compared the overall percentage of errors made by the participants in the numerosity judgment conditions of the two experiments by means of

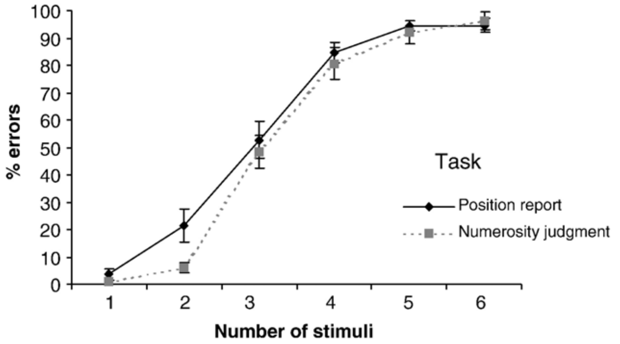

Fig. 3 – Mean error rates in the numerosity block of trials and in the spatial report block of trials as a function of the number of tactors activated in Experiment 3. Error bars represent the standard errors of the means.

an independent samples *t*-test. This test failed to reveal any significant difference [$t(20)=-.328$; $p=0.74$], thus ruling out the possibility that the order of presentation of the two experimental blocks affected the results of Experiment 1 and 2.

2.3. *Experiment 3*

The results obtained in Experiment 3 are shown in Fig. 3. This graph shows that the number of participants' errors increases with the number of stimuli presented in the display regardless of whether they had to perform a numerosity judgment or a position report task. The mean percentage of errors in the numerosity judgment block was submitted to a repeated measures ANOVA with the factors of numerosity (6 levels) and task (numerosity judgments vs. position report). The analysis revealed a significant main effect of numerosity [$F(5,65)=437.9$; $p<0.0001$] and a borderline-significant effect of task [$F(1,13)=4.18$; $p=0.06$]. The analysis failed to reveal any significant interaction between these two factors [$F(5,65)=1.32$; $p=0.26$]. A post hoc LSD test on the main effect revealed significant differences between each pair of consecutive numerosities (all $p<0.0005$), with the exception of the comparison between 5 and 6 stimuli ($p=0.41$). In both tasks, the number of errors made by participants increased as the number of stimuli composing the display increased (see Fig. 3), once again consistent with the results obtained in previous studies (e.g., Gallace et al., 2006b, 2007a). Error rates in the numerosity judgments task were lower than in the position report task.

3. Discussion

3.1. *Experiment 1*

The results of Experiment 1 clearly show that information regarding the tactile stimuli presented in parallel across the body surface, although not available for full explicit report, can nevertheless still be accessed to some degree using a partial report procedure. In particular, whereas only 3 stimuli could be identified correctly using a numerosity judgment task, up to 5 stimuli could be reported when a partial report procedure was adopted instead (corresponding to a 66.6% improvement in participants' performance). That is, we replicated for the first time (in the tactile modality), a result that has frequently been obtained previously using visual displays (e.g., Coltheart, 1980, 1983; Di Lollo, 1977; Neisser, 1967; Sperling, 1960). Our results also show that a maximum of 5 items can be stored in tactile STM. Indeed, when the displays were composed of 6 stimuli, participants' performance was at chance levels for both the numerosity judgment and for the partial report tasks.

It is worth noting here that the overall intensity of the display may have played a certain role in the number of positions reported by participants in the numerosity task. Indeed, a previous study that used a very similar setup showed that participants' numerosity judgments are, at least in part, affected by the increase in the intensity of the display presented (the higher the intensity of the display, the better the participants' performance; Gallace et al., 2006a). Note, however, that the results of Gallace et al.'s study also showed that participants do not base their numerosity judgments solely on the intensity of the stimuli presented (e.g., if a single stimulus is presented at an intensity equivalent to that of 7 stimuli, participants are not biased to report a numerosity judgment close to 7 stimuli).

The results of Experiment 1 also show that information regarding the tactile stimuli presented across the body surface are available for report, at least when using partial report procedures, for up to 1000 ms. It is, however, worth noting here that for displays composed of 5 stimuli, a post-stimulus probe at 1000 ms only just allowed access to the unreported information regarding the tactile display. This result would appear to suggest that the duration and capacity of the short-term tactile representations for tactile stimuli may be mutually related. That is, increasing the amount of information to be stored may result in a more rapid decay of such information.

3.2. *Experiment 2*

The results of Experiment 2 showed that increasing the SOA between the presentation of the tactile display and the visual probe resulted in an increase in the number of errors made by participants in the partial report task. In particular, the performance of participants under conditions in which the displays were composed of 2–4 stimuli fell to chance levels at the longer SOAs (i.e., 5000 ms). Note, however, that in Experiment 1, where shorter SOAs were used, participants' performance was above chance for all of these numerosities. This result clearly suggests that the short-term representations of tactile information presented across the body surface decay at a speed that is dependent on the number of stimuli presented in the display. For example, when 5 stimuli are distributed across the body surface, the representation of the stimuli is no longer accessible for report 1000 ms after the offset of the tactile display. By contrast, the representations of displays composed of 3 and 4 stimuli are no longer available for explicit report 5000 ms after the offset of the stimuli. This result represents an important difference from previous studies of visual short-term representations. Indeed, we are not aware of any previous study in which the duration of the sensory memory for visual stimuli has been investigated as a function of the amount of information stored and/or presented. The results of Experiment 2, obtained when the partial report block of trials was presented before the numerosity judgments task, also ruled out the possibility that any difference between the two tasks obtained in Experiment 1 could have been related solely to the order of presentation of the experimental blocks (i.e., to some kind of learning effect).

It is worth noting here that participants' performance with displays composed of 2 stimuli for SOAs of 100 ms appears to be worse than that obtained under conditions in which 3 and 4 stimuli were presented in the displays. This result might be related to an attempt to use verbal coding strategies when relatively longer SOAs are available for response within the same block of trials (i.e., 100–5000 in Experiment 2 as compared to 20–1000 in Experiment 1). That is, having realized that more time is available between the presentation of the display and the probe in the majority of the trials, participants might have attempted to codify the position of the 2 stimuli by using verbal labels instead. This possible interpretation seems to find support in the observation that when 2 stimuli were presented in the display, the participants' errors did not differ significantly across the range of SOAs adopted (as for 1 stimulus presented in Experiment 1). The role of verbal strategies in the encoding and recollection of tactile information should be investigated in future research. Specifically, tactile memory should be tested under conditions in which verbal encoding of the stimuli is prevented by using verbal rehearsal (e.g., Gilson and Baddeley, 1969).

In summary, the results of Experiment 2 clearly confirm the existence of short-term representations of tactile information that are subject to rapid decay, similar to those observed when visual stimuli are presented (e.g., Sperling, 1960).

3.3. *Experiment 3*

The pattern of results that emerged from the analysis of Experiment 3 support the view that numerosity judgments are no more difficult than the full report of the spatial positions from which the tactile stimuli were presented. By contrast, our results highlight the fact that the full report of spatial positions led to a borderline-significant greater number of errors than were observed in the numerosity judgment task. Note that this result is not particularly surprising given that whereas in the numerosity judgment task there is only one possible source of error (i.e., the number of stimuli presented in the display), the position report task can be affected by two possible sources of error, one regarding the *number* of stimuli presented in the display and the second regarding the *localization* of the stimuli. In summary, Experiment 3 suggests that the comparisons between numerosity judgment and partial report in Experiments 1 and 2 provide a valid means to quantify the short-term persistence of tactile representations.

On the basis of the results obtained in Experiments 1 and 2, one might have expected to find a significant interaction between the number of stimuli presented and the task performed by participants. Specifically, given that reporting the position of the stimuli presented in the display requires more time than simply reporting the number of stimuli that had been presented, the rapid decay of the representation of the tactile stimuli (and, in particular, of displays composed of larger numbers of stimuli) should have affected the former of these two tasks more than the latter. Surprisingly, however, the results of Experiment 3 showed no such trend (see also Fig. 3), perhaps suggesting that the rapid decay of tactile information is not the sole factor to have affected the results of Experiments 1 and 2 (see also General discussion).

4. General discussion

The results show that representations of tactile stimuli are stored in the cognitive system for a limited amount of time, even when not available for explicit report. These representations can be accessed before they decay using a partial report procedure, consisting of the presentation of a post-stimulus probe in one of the previously stimulated positions. This result appears, prima facie, to be similar to those obtained in earlier visual studies by Sperling (1960). However, a closer observation of the data obtained in the experiments reported here highlights the presence of a number of important differences between tactile, as compared to visual, short-term representations investigated in the extant literature. Specifically, it appears that much more information can be reported using partial report (as compared to a full report) procedures in the visual modality (e.g., Sperling reported a 180% increase in the number of stimuli recalled) than by using partial report procedures in the tactile modality (e.g., 66.6% increase; see Experiment 1; for a similar improvement in performance when using the partial report of auditory stimuli, see Darwin et al., 1972).

It has been argued elsewhere (see Gallace and Spence, 2007) that any difference between the capacity limit of tactile as compared to visual information processing might be related to a number of different factors: (a) people have been shown to have a lower spatial discrimination threshold for tactile than for visual stimuli; (b) touch has been considered a relatively more primitive sensory modality (e.g., Gregory, 1967); and (c) participants are more used to processing visual information than tactile information, especially when the tactile information is presented across the body surface as in the present study. On the basis of these considerations, one might therefore think that transient neural representations of tactile events have a lower capacity, duration, and/or accessibility as compared to the representation of visual events. It will therefore be interesting in future research to investigate tactile short-term representations in participants who have been trained to perceive tactile stimuli distributed across their body surface and/or in congenitally blind participants (see Arnold and Heiron, 2002; Craig, 1977; Craig and Belser, 2006; Heller, 1987, 1989). Moreover, it will also be of interest to compare the performance of the same group of participants under conditions in which the stimuli are presented on the fingertips versus on the rest of the body surface (cf. Gallace et al., in press). Given that the organization of tactile memories has been shown to replicate that found in the primary sensory areas (i.e., SI) of the brain (see Harris et al., 2001), one might expect to find differences in durations and/or capacity of short-term tactile representations when the displays are presented on the fingertips as compared to conditions in which the displays are presented on the rest of the body surface.

It is worth noting here that only one level of stimulus intensity was used in the present study (cf. Gallace et al., 2006b). One might therefore wonder if different results might have been obtained had the intensity of the stimuli been increased. Indeed, in a previously published study of tactile numerosity judgments, Gallace et al. (2006b) showed that participants' task performance improved when the overall stimulation intensity level was increased. On the basis of such results, one might expect that the duration of short-term tactile representations increases with the intensity of the stimuli presented in the display (with higher intensities perhaps leading to results more similar to those reported in the visual perception literature). This topic surely deserves further investigation.

The possibility should also be borne in mind that the previous visual studies cannot be easily compared with the present tactile study. In particular, Sperling (1960) investigated visual sensory representations using visually presented letters, whereas in the present study we only used stimuli that would have been difficult to verbalize. Moreover, in order to test the full report of the stimuli presented in the displays, a target detection task was used in the experiments reported here. By contrast, Sperling used a discrimination task, perhaps leading to a larger number of errors in his classic study and therefore larger differences between performance in the full and partial report tasks.

The rate of decay of the representations of tactile stimuli investigated in the present study seems to be different from the rate of decay of the sensory representations investigated previously in the visual modality. For example, increasing the SOA from 20 to 1000 ms produced only very small increases in the error rates when up to 4 stimuli were presented (see our Experiment 2). This SOA dependence was much lower than in the classic visual partial report studies (see Sperling, 1960).

The fact that partial report still offers better than chance performance (as compared to a numerosity judgment task) for relatively long SOAs suggests that rapidly decaying iconic storage may not be the only process that accounts for the results reported in the present study. In fact, one might suggest the presence of two processes here, one SOA dependent and the other not. The first reflects the rapid decay of a short-term tactile representation, analogous to that investigated previously in vision. The other might be related to the fusion of individual elements into an overall tactile pattern. Indeed, whereas in the visual arrays used by Sperling (1960), each item (letter) had a clear individual identity and meaning, the stimuli used in the tactile arrays reported here differed solely in terms of their location. They might somehow fuse to form a compound pattern, whose elements cannot be easily individuated (also resulting in the poor performance reported in recent tactile numerosity judgment studies; e.g., Gallace et al., 2006b, 2007a, in press). The visual probe might therefore work by allowing the individual elements, stored in some tactile representation prior to fusion or grouping, to be retrieved. Interestingly, this process of individuating the elements in the display seems to be possible only by means of exogenous (i.e., stimulus driven) rather than endogenous (i.e., voluntary) procedures. This possibility should be investigated in future research, perhaps by comparing participants' performance in visual and tactile memory tasks in which the stimuli composing the displays for both sensory modalities can only be coded in terms of their spatial, rather than verbal, attributes.

One might also consider that the differences between the results reported here and those reported previously using visual stimuli (together with the presence of somewhat inconsistent pattern of results in the present study) may be related to the lower spatial resolution of touch as compared to vision. Note, however, that the spatial resolution of touch has been shown to be far superior to the minimum spatial separation used in our research (e.g., see Weinstein, 1968) ruling out this possibility as the sole explanation for the obtained results. Alternatively, however, one might consider the fact that tactile stimuli presented in parallel over the body surface have been shown to lead to reciprocal masking effects (see Alluisi et al., 1965; Gallace et al., 2006b). The presence of masking between different body locations (thought to be attributable to central rather than peripheral processes; e.g., Alluisi et al., 1965; Gallace et al., 2006b, 2007a) might have contributed to participants' confusion at the level of stimulus encoding, resulting in the inconsistencies in certain of the patterns of results reported here. In line with this view, it is worth noting that the presence of masking has also been shown to impair visual and acoustic short-term sensory memory (e.g., for a review, see Coltheart, 1980).

Interestingly, some studies have suggested that the decay of iconic memory involves the loss of "spatial" information about the items, not a loss of information concerning item identity (e.g., Mewhort et al., 1981; see also Mewhort and Campbell, 1978; Mewhort and Leppmann, 1985; Mewhort et al., 1984; Townsend, 1973; cf. Campbell and Mewhort, 1980). In particular, Mewhort and Leppmann (1985) presented the participants in one of their experiments with a row of random letters for a duration of 50 ms; after a variable SOA, they asked them whether or not a named letter had been presented in the display. In a second experiment, the named letter was always present in the display and the participants were asked to identify its location. They reported that the accuracy of participants' responses was independent of the SOA in their first experiment but dropped rapidly as the SOA increased in their second experiment. The authors concluded that the information that rapidly decays in iconic memory experiments relates to the spatial, rather than to the identity, characteristics of the stimuli presented. This result therefore suggests that the visual probe used in the experiments reported here might have contributed to reactivate or facilitate the access to tactile information as a function of its spatial coincidence with the target stimulus.

Recent results emerging from neuroimaging research might be taken to support this suggestion. In particular, Ricciardi et al. (2006) asked the participants in their study to compare successively presented two- and three-dimensional tactile matrices while measuring the cortical activity correlated with the retention and recognition of the information presented. Interestingly, they also compared a tactile working memory task with a visual working memory task using exactly the same experimental procedures. The results of their fMRI study indicated that similar fronto-parietal networks were recruited during spatial working memory tasks in both the visual and tactile modalities. Ricciardi et al. therefore suggested that common cerebral regions may subserve the

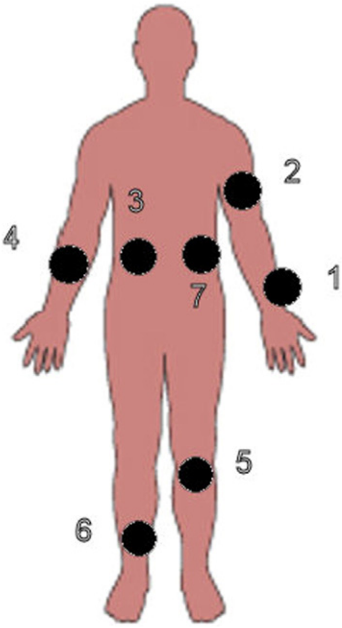

Fig. 4 – Positions on the body surface where the tactors and LEDs were placed: (1) left wrist; (2) midway between the elbow and the shoulder on the left arm; (3) on the waistline, to the right of the body midline; (4) just above the right elbow; (5) just below the left knee; (6) midway between the ankle and knee on the right leg; and (7) on the waistline to the left of the body midline (this position was not used in Experiment 3). Note that the homologous positions on the waistline (i.e., positions 3 and 7) were never stimulated on the same trial.

generation of a higher order representation involved in the memory of both visual and tactile information (leading to the idea of a supramodal organization for mental memory representations in the brain). Therefore, we believe that further research should be carried out in order to address the possibility that amodal and/or multisensory short-term representations of spatial information are stored in the cognitive system.

Whatever the explanation for the effect of the visual probe on the report of tactile information found in the present study turns out to be, our results nevertheless offer the first clear evidence for the presence of short lasting tactile representations of stimuli presented in parallel across the body surface. Specifically, our results show that the neural representations of tactile stimulus displays can be accessed by means of a post-stimulus probe, before their decay, also when not available for complete report.

5. Experimental procedures

5.1. *Experiment 1*

5.1.1. *Participants*

Eleven right-handed participants (3 males and 8 females) took part in this experiment as volunteers (mean age of 19 years, range of 18–26 years). All of the participants reported normal tactile perception and had normal or corrected to normal vision. The experiment took approximately 25 min to complete and the participants received course credit in return for their participation. The experiments reported here were non-invasive and had ethical approval from the Department of Experimental Psychology, University of Oxford, and were performed in accordance with the ethical standards laid down in the 1991 Declaration of Helsinki.

5.1.2. *Apparatus and materials*

The participants sat on a chair for the duration of the experiment. The vibrotactile stimuli were presented by means of seven 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 participant's body on top of any clothing that they happened to be wearing by means of Velcro strip belts. Green LEDs were mounted at the same position as each tactor but on the other side of the belts (for the position of the tactors and LEDs on the body, see Fig. 4; cf. Gallace et al., 2006b, 2007a). The vibrators were driven by means of a custom-built 9-channel amplifier circuit (Haptic Interface Laboratory, Purdue University, Indiana, USA) that drove each tactor independently at 290 Hz (close to its resonant frequency). The LEDs were driven by means of a custom-built relay box.

The activation of each tactor and LED was controlled by a computer. The intensity of each tactor was adjusted individually at the beginning of the experiment, so that each vibrotactile stimulus could be perceived clearly, and all of the tactile stimuli were perceived to be of a similar intensity. The amplification levels for the tactors were kept at these individually adjusted levels throughout. White noise was presented over closed-ear headphones at 70 dB(A) to mask any sounds made by the operation of the vibrotactile stimulators and relay box. A 65×90 cm mirror was placed 100 cm in front of the participant (from the upper edge of the mirror to the participant's eyes) to allow them to see all of the LEDs attached to their own body. The correct discrimination of the visual stimuli presented from each body location was assessed at the beginning of the experiment for each participant. The experiment was composed of two blocks of trials. In the first block of trials (numerosity judgments), the stimuli consisted of 200-ms-long vibrations delivered through a variable number of tactors. A different random subset of between one and six tactors was activated on each trial. The second block of trials (partial report) was composed as follows: between one and six vibrotactile stimuli were presented as before. After a variable interval from the onset of the tactile display, one of the LEDs on the participant's body was illuminated for 100 ms. Four intervals (SOAs) between the tactile display and the onset of the light were used: 20, 100, 300, and 1000 ms. The partial report block of trials was divided in two equal parts, separated by a short break.

5.1.3. *Procedure*

In the numerosity block of trials, the participants were instructed to press a numerical key on a computer keyboard corresponding to the perceived number of tactors on each trial. Each number of tactors (i.e., 1–6) was presented 12 times giving rise to a total of 72 trials for each participant. In the partial report block of trials, the participants were required to press one of two keys on a computer to indicate whether or not a tactile stimulus had just been presented in the position indicated by the light (i.e., hereafter "the probe"). The participants in this unspeeded task were instructed to respond as accurately as possible. Each trial was terminated if no response was made within 6000 ms of the onset of the probe. No feedback was given regarding the correctness of the participant's response. For each number of stimuli composing the display (1–6) and for each target-probe SOA (20, 100, 300, 1000 ms), 14 trials were presented giving rise to a total of 336 trials completed by each participant. In 50% of the trials, the probe was presented in a position that had been previously stimulated by one of the tactors; whereas in the remaining trials, the light was randomly presented in one of the other unstimulated positions.

5.2. *Experiment 2*

5.2.1. *Participants*

Eleven new right-handed participants (2 males and 9 females) took part in this experiment (mean age of 20 years, range of 18–24 years). All of the participants reported normal tactile perception and had normal or corrected to normal vision. The experiment took approximately 40 min to complete and the participants received course credit in return for their participation.

5.2.2. *Apparatus, materials, design, and procedure*

The experimental set-up and procedure were exactly the same as in Experiment 1 with the following exceptions: In the partial report block, the SOAs between the vibrotactile patterns and the visual probe were now 100, 500, 2000, or 5000 ms; the number of vibrotactile stimuli composing the display in each trial was 2, 3, 4, or 5, for the partial report blocks of trials. Displays consisting of 1 and 6 stimuli were dropped from the partial report block of Experiment 2, given that they resulted in ceiling and floor level performance, respectively, in Experiment 1. Twelve stimuli were presented for each numerosity and for each SOA giving rise to a total of 192 trials completed by each participant in the partial report block. The partial report block was now presented before the numerosity judgment block, so that perceptual learning could not explain any superior performance in the partial report block.

5.3. *Experiment 3*

5.3.1. *Participants*

Fourteen new right-handed participants (7 males and 7 females) took part in this experiment (mean age of 22.5 years, range of 19–30 years). All of the participants reported normal tactile perception and had normal or corrected to normal vision. The experiment took approximately 30 min to complete and the participants received a £5 gift voucher in return for their participation.

5.3.2. *Apparatus, materials, design, and procedure*

The experimental set-up and procedure were exactly the same as in Experiment 1 with the following exceptions: The experiment was composed of two blocks of trials. In one block of trials (numerosity judgments), the stimuli consisted of 200 ms long vibrations delivered to a variable number of tactors (1 to 6). The other block of trials (position report) was composed as follows: A tactile display composed of 1 to 6 vibrotactile stimuli was presented on the participants' body for 200 ms. Immediately after the offset of the tactile display, a body silhouette, representing the participant's body as seen when reflected in a mirror (i.e., the right side of participant's body was mapped on the right side of the silhouette, and vice versa for the left side of the body), was presented on a 37×31 cm PC screen placed 50 cm in front of the participant. The order of presentation of the two blocks of experimental trials was counterbalanced across participants.

Different numbers (1–6) drawn on different parts of the body silhouette corresponded to the locations on the participant's body where the tactors were mounted (see Fig. 4; note, however, that with respect to Fig. 4, the positions of the stimuli in the silhouette were left-right reversed and position 7 was never stimulated and hence was not represented in the silhouette). The participants had to select those locations where the stimuli had been presented on the body silhouette by pressing the corresponding number on a PC keyboard. Each trial was terminated when the participant, after selecting the stimulated position on the body silhouette, pressed the "Escape" key on the PC keyboard. No time constraints were placed on the completion of this task. Twelve stimuli were presented for each numerosity and for each block of trials, giving rise to a total of 144 trials completed by each participant.

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