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Numerosity judgments for tactile stimuli distributed over the body surface

Alberto Gallace¶, Hong Z Tan§, Charles Spence
Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK;
e-mail: alberto.gallace@psy.ox.ac.uk; ¶ Also at Dipartimento di Psicologia, Università degli Studi di Milano-Bicocca, 1 piazza dell'Ateneo Nuovo, I 20126 Milan, Italy; § Haptic Interface Research Laboratory, Purdue University, West Lafayette, IN 47907, USA
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Abstract. A large body of research now supports the claim that two different and dissociable processes are involved in making numerosity judgments regarding visual stimuli: subitising (fast and nearly errorless) for up to 4 stimuli, and counting (slow and error-prone) when more than 4 stimuli are presented. We studied tactile numerosity judgments for combinations of 1 – 7 vibrotactile stimuli presented simultaneously over the body surface. In experiment 1, the stimuli were presented once, while in experiment 2 conditions of single presentation and repeated presentation of the stimulus were compared. Neither experiment provided any evidence for a discontinuity in the slope of either the RT or error data suggesting that subitisation does not occur for tactile stimuli. By systematically varying the intensity of the vibrotactile stimuli in experiment 3, we were able to demonstrate that participants were not simply using the 'global intensity' of the whole tactile display to make their tactile numerosity judgments, but were, instead, using information concerning the number of tactors activated. The results of the three experiments reported here are discussed in relation to current theories of counting and subitising, and potential implications for the design of tactile user interfaces are highlighted.

1 Introduction

Numerosity judgments have long been studied in vision (eg see Atkinson et al 1976a; Jevons 1871; Kaufman et al 1949; Lechelt 1971; Saltzman and Garner 1948; Sathian et al 1999; Weiss 1965). In a typical study, participants are briefly presented with a random array of visual stimuli and asked to report how many stimuli they perceive. The stimuli to be counted are sometimes presented in isolation, or else are distributed amongst an array of distractors. The physical parameters of the array, and the presentation time of the stimuli, are also frequently varied. Normally, the reaction time (RT) and accuracy of participant's responses are collected as performance measures (see Trick and Pylyshyn 1993, for a review).

Studies of visual numerosity judgments have revealed differences in both the accuracy and latency of responses when small versus large numbers of items are compared (see Trick and Pylyshyn 1993). When small numbers of items are presented (typically between 1 and 4 stimuli), they appear to be processed very rapidly and nearly perfectly (eg Atkinson et al 1976a). Increasing the number of items presented above 4 typically produces a large increase in both average response latencies and error rates, giving rise to a discontinuity in the slope of the latency and error functions (see figure 1; Atkinson et al 1976a). Such results have been interpreted by many authors as providing evidence for the existence of two qualitatively different enumeration processes, one specialised for small numbers of items and the other specialised for larger numbers of items. The former is known as '*subitising*' and appears to be fast, accurate, and pre-attentive, while the latter is thought to reflect '*counting*', and appears to be slow, error-prone, and attentionally demanding (eg Kaufman et al 1949; Mandler and Shebo 1982; Peterson and Simon 2000).

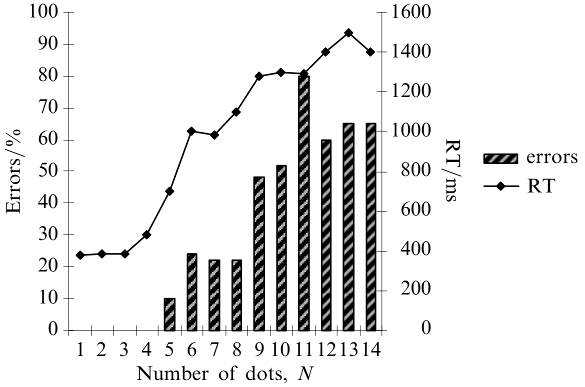

Figure 1. Mean error rates and RTs as a function of the number of visual stimuli presented (ie dots on a screen) in a prototypical visual numerosity judgment study. Modified from Atkinson et al (1976).

While differences in performance between subitising and counting appear to be unaffected by changes in the size of the visual stimuli that have to be enumerated (eg Trick and Pylyshyn 1993), changing other stimulus parameters has been shown to affect counting and subitising differently. For example, changing the colour, orientation, and/or grouping of targets to be enumerated amongst an array of distractors affects both the latency and accuracy of counting but not of subitising (eg Atkinson et al 1976b). Counting typically requires several eye movements on the part of the participant in order to locate the stimuli, whereas subitising does not (eg Atkinson et al 1976a; Simon and Vaishnavi 1996). Counting is influenced by the spatial arrangement of the objects (ie responses are facilitated under conditions where the stimuli can be perceptually grouped), while subitising is not (eg Atkinson et al 1976b; van Oeffelen and Vos 1983).

Recent neuropsychological evidence has also provided support for the claim that subitising and counting may be mediated by separate and dissociable neural mechanisms (eg Dehane and Cohen 1994; Pasini and Tessari 2001). For instance, Dehane and Cohen reported that patients with right parietal lesions who are affected by simultagnosia sometimes demonstrate intact subitising together with impaired counting. By contrast, intact counting and impaired subitising has been reported in an acalculic patient by Cipollotti et al (1991). Nevertheless, despite these examples, Piazza et al (2002) have argued that strong and convincing evidence for a neuropsychological double dissociation between counting and subitising has yet to be reported.

The vast majority of numerosity studies published to date have used visual stimuli. Far fewer studies have attempted to investigate people's ability to count stimuli presented in other sensory modalities, such as audition or touch. Subitising effects have been demonstrated in audition by Gert and Joos (1979) when participants had to count sequences of 2 – 7 sequentially presented tones (see also John 1972), and by Kashino and Hirahara (1996) when participants had to count the number of voices presented simultaneously. These results suggest that subitising is not an exclusively visual phenomenon, since the enumeration of stimuli presented in other sensory modalities, such as audition, also appears to be affected.

Numerosity judgments have also been studied in touch by Ginsburg and Pringle (1988). They asked participants to scan between 10 and 36 cardboard discs mounted on a plane surface with their hand for 5 s. Ginsburg and Pringle's results showed a monotonic increase in the number of stimuli reported by participants as a function of the number of stimuli presented. It should, however, be noted that performance was by no means perfect, with participants tending to underestimate the number of stimuli presented. What is more, given that Ginsburg and Pringle presented a minimum of

10 stimuli on every trial, their results do not provide any evidence with regard to the question whether or not small numbers of tactile stimuli can be enumerated by subitisation. Therefore, in the present study, we investigated tactile numerosity judgments by simultaneously presenting between 1 and 7 vibrotactile stimuli distributed over the body surface. Our primary aims were to determine whether subitisation occurs in touch and to explore the possible limitations on tactile cognitive processing when stimuli are presented over the body surface.

Exploring the perception of a different number of stimuli distributed over the body surface and the factors that can successfully improve it is also of great importance, given the recent interest in using tactile interfaces for human operators in various applied settings (eg van Erp 2000; van Erp and van Veen 2004; Ho et al 2005; Rochlis and Newman 2000; Rupert 2000; Sorkin 1987; Spence and Driver 1999).

2 Experiment 1

2.1 *Methods*

2.1.1 *Participants.* Ten right-handed participants (three males and seven females) took part in this experiment as paid volunteers (mean age 26 years, range 21 – 35 years). All of the participants reported normal tactile perception. The experiment took approximately 25 min to complete and all of the participants received a UK £5 gift voucher in return for their participation. The experiments reported here were noninvasive 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.

2.1.2 *Apparatus and materials.* The experiment was conducted in a normally illuminated room. The participant sat comfortably on a chair for the duration of the experiment. The vibrotactile stimuli were presented by means of 7 resonant-type tactors (Part No VBW32, Audiological Engineering Corp., Somerville, MA, USA), with 1.6 cm × 2.4 cm vibrating surfaces. The tactors were placed on the participant's body on the top of his/her clothes by means of Velcro strip belts. The positions of the tactors on the participant's body (see figure 2) were as follows: left wrist (tactor 1); just below the

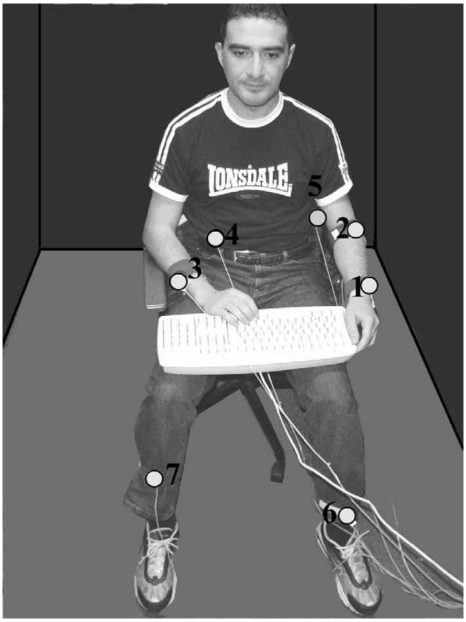

Figure 2. Positions on the body surface where the tactors were placed: (1) left wrist; (2) just below the left elbow; (3) midway between the wrist and elbow on the right arm; (4) on the waistline, to the right of the body midline; (5) on the back, to the left of the body midline; (6) just above the left ankle; and (7) midway between the ankle and knee on the right leg. Note that these positions were chosen to ensure that homologous sites on both sides of the body were never stimulated.

left elbow (tactor 2); midway between the wrist and elbow on the right arm (tactor 3); on the waistline, to the right of the body midline (tactor 4); on the back, to the left of the body midline (tactor 5); just above the left ankle (tactor 6); and midway between the ankle and knee on the right leg (tactor 7). The participants were not able to see any of the tactors directly under the belts. The 7 body sites were selected on the basis of their relative 'salience' in order to minimise localisation errors (cf Geldard 1968; Geldard and Sherrick 1965). The vibrators were driven by means of a custom-built 9-channel amplifier circuit that drove each tactor independently at 290 Hz (close to its resonant frequency). The intensity and the on/off timing of each tactor were controlled through the serial port of a laptop computer running custom software written in Matlab 6.0. White noise was presented over closed ear headphones at 70 dBA to mask any sounds made by the operation of the vibrotactile stimulators.

The intensity of each tactor was adjusted individually at the beginning of the experiment. The participants were requested to judge whether the intensity of each of the vibrotactile stimuli was high enough to be perceived clearly. The participants were also requested to match the intensities of the 7 tactors, so that all the stimuli were perceived to be of similar intensity. The participants adjusted the tactor intensity in the same order of tactor 1 to 7. The amplification levels for the 7 tactors were kept at their individually chosen levels throughout the experiment. On each trial, the stimuli consisted of 200 ms vibrations delivered through a variable number of tactors. The number of tactors activated on each trial varied randomly between 1 and 7. For each number of tactors, different activation patterns were chosen randomly among all of the possible combinations (eg when 1 tactor was activated, there were 7 possible patterns; when 7 tactors were activated, only 1 pattern of stimulation was possible).

2.1.3 *Procedure.* The participants were instructed to press the numeral key on a computer keyboard corresponding to the perceived number of tactors on each trial. Participants were requested to be as accurate as possible in their responses. They were also informed that their response times would be collected and that there was a time limit for their responses. The trial was terminated after the participant's response or after 4000 ms had elapsed from the onset of the stimulus. Each number of tactors (ie 1 – 7) was presented 35 times giving rise to a total of 245 trials for each participant. Participants were aware that the maximum number of stimuli that could be delivered was 7, and they were only allowed to make responses in the range of 1 to 7.

2.2 *Results*

For each participant, the mean reaction time (RT), percentage of errors, and the mean response given (ie 1 – 7) to each of the number of stimuli presented were collected (see figure 3). Trials in which participants failed to give a response within 4000 ms of stimulus onset were not included in any of the data analyses (less than 4% of trials overall). Each of the three performance measures was submitted to a repeated-measures analysis of variance (ANOVA) with the factor of numerosity (7 levels: 1 to 7 tactors activated). These analyses revealed a significant main effect of the number of tactors activated in the RT, error, and mean response data ($F_{6,54} = 9.48$, $p < 0.001$; $F_{6,54} = 140.6$, $p < 0.001$, and $F_{6,54} = 140.7$, $p < 0.001$, respectively), with response latencies, error rates, and the mean response given all increasing as the number of tactors activated increased.

The mean RTs and the average number of errors for each number of tactors presented was then calculated for the group of participants on the basis of the individual participant's averaged data and submitted to a linear regression analysis. This analysis allowed us to verify whether or not a monotonic relationship existed between the number of tactors activated and the two performance measures. The regression analysis revealed a significant linear relationship between the number of tactors activated and the mean RT, and between the number of tactors presented and the mean error

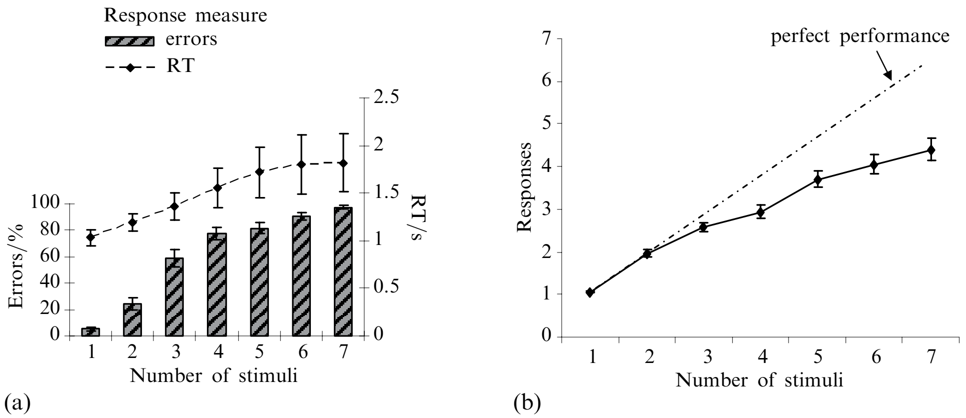

Figure 3. (a) Mean error rates and RTs in experiment 1 as a function of the number of tactors activated. (b) Mean number of tactors reported by participants in experiment 1 as a function of the number of tactors activated. Error bars represent ±1 SEM.

rate ($F_{1,6} = 138.5$, $p < 0.001$; and $F_{1,6} = 105.9$, $p < 0.001$, respectively). These results highlight the lack of any discontinuity between tactile numerosity judgments in the subitising and counting ranges.

2.3 *Discussion*

The results of experiment 1 revealed no evidence for a discontinuity in the slope of the functions fitted to the performance data (see figure 3), thereby arguing against the presence of a subitising effect for tactile numerosity judgments. Both the RT and error data appeared to be linearly related to the number of tactors presented [see Ginsburg and Pringle (1988) for similar results when participants had to count between 10 and 36 stimuli that were scanned haptically]. The lack of any subitising effect might be suggestive of an attentional limitation in enumerating multiple tactile stimuli presented over the body surface.

The overall level of performance in experiment 1 was quite poor. Error rates, although mostly below the chance level of 85.7% errors, became quite high (above 50% errors) as soon as the number of tactors activated increased above 2. There are several possible reasons for such poor performance. First, one might argue that the decline in performance seen as the number of tactors activated increased might simply reflect a masking effect (eg Kirman 1973). Indeed, previous studies have shown that masking effects increase as the number of stimuli presented increases (eg Gilson 1969; Loomis 1981). However, masking effects decrease monotonically with increasing interstimulus distance (eg Kekoni et al 1990; Sherrick 1964), and are much more prevalent when stimuli are presented ipsilaterally than when they are presented contralaterally (eg Finger and Levin 1972). Given that we used a wide spacing of vibrotactile stimulations over the body surface (the minimum separation between any two tactors was approximately 20 cm), and given that we never stimulated homologous sites on both sides of the body (cf Geldard 1968; Geldard and Sherrick 1965; see figure 2), it would seem unlikely that masking alone could account for the poor performance observed in experiment 1.

A second possible explanation for the poor performance seen in experiment 1 is that it might reflect the phenomenon of 'apparent location' (eg von Békésy 1959; Kotovsky and Bliss 1963), whereby when two discrete spatially separated vibrations are presented simultaneously on the skin they can sometimes summate and be perceived as a single vibration located somewhere between the 2 vibrators. This kind of stimulus summation effect has been shown to occur most frequently when the pressure of the 2 tactile stimuli is different and/or when the 2 stimuli are presented slightly asynchronously (eg von Békésy 1959).

Moreover, to date, the effect has only been demonstrated when vibratory stimuli were separated by less than 12 cm (von Békésy 1959; Kotovsky and Bliss 1963). Given that the smallest intervibrator separation used in experiment 1 was 20 cm, spatial summation effects would therefore also appear to provide an unlikely explanation for the poor performance of participants (cf Geldard 1968; Geldard and Sherrick 1965).

We believe, instead, that the most likely explanation for the poor performance reported in experiment 1 may be related not to low-level sensory interactions between the vibratory stimuli (such as masking or interstimulus summation) but, instead, to higher level cognitive/attentional limitations. In particular, we believe that the limited time that was available (200 ms) for participants to shift (or disengage; see Posner 1980) their attention between/from different body sites may have been insufficient for them to enumerate the tactile stimuli successfully. It has been demonstrated previously that it takes people significantly longer to shift their attention away from tactile stimuli than from either visual or auditory stimuli (eg Spence et al 2001a, 2001b). Moreover, shifts of tactile attention through space (or across the body surface) also appear to be slower than for spatial shifts of attention between either auditory or visual stimuli (eg Lakatos and Shepard 1997; Mondor and Zatorre 1995; Shulman et al 1979; Yantis 1988). Lakatos and Shepard have demonstrated that up to 500 ms may be required by people to shift their attention between tactile stimuli presented to distant body locations (such as between the wrists when the arms are outstretched).

Given these findings, one might wonder whether the 200 ms duration of tactile stimulus presentation in experiment 1 would have given participants sufficient time to shift their attention sequentially between the different body locations in order to enumerate the tactile stimuli successfully (before the display was terminated) when several tactile stimuli were presented at the same time. In order to address this issue, we gave participants in our next experiment more time to shift their attention between stimulus locations in a repeated-presentation block, by presenting the tactile stimuli repeatedly for 5 s on each trial (cf Ginsburg and Pringle 1988). We compared performance under these conditions to that seen following a single 200 ms stimulus presentation (as used in experiment 1). Given the increased duration of stimulus presentation in the repeated-presentation condition of experiment 2, we reasoned that participants should have had sufficient time to shift their attention sequentially between different locations on their body (cf Lakatos and Shepard 1997), and hence it seemed likely that their performance would improve above the level seen in experiment 1. However, if the poor performance in experiment 1 was solely attributable to some form of low-level sensory interactions (eg interstimulus masking or stimulus summation) then presenting the stimuli for longer should not lead to any appreciable improvement in performance.

3 Experiment 2

3.1 *Methods*

3.1.1 *Participants.* Ten right-handed participants (four males and six females) took part in this experiment as paid volunteers (mean age 26 years, range 21 – 33 years). All of the participants reported normal tactile perception. The experiment took approximately 50 min to complete and all of the participants received a UK £5 gift voucher in return for their participation.

3.1.2 *Apparatus, materials, design, and procedure.* The experimental setup and procedure were exactly the same as in experiment 1 with the following exception. The experiment was now composed of two blocks of experimental trials. In the first block, the stimuli were presented only once for 200 ms on each trial (just as in experiment 1). In the second block of trials, the stimuli were repeatedly turned on and off for 200 ms with an interstimulus interval of 200 ms for a total stimulus duration of 5000 ms.

Responses were only collected after the offset of the stimuli and RTs were measured from stimulus offset. The matching of stimulus intensity occurred only once at the start of each participant's experimental session. Each number of tactors (ie 1 – 7) was presented 35 times in each block of trials giving rise to a total of 490 trials for each participant.

3.2 *Results*

Trials in which participants failed to give a response before the trial was terminated (less than 4% of trials overall) were not analysed. The mean RTs, percentages of errors, and the mean numerical responses are presented in figure 4. Each of the three response measures was submitted to a repeated-measures ANOVA with the factors of numerosity (7 levels) and block (single presentation versus repeated presentation).

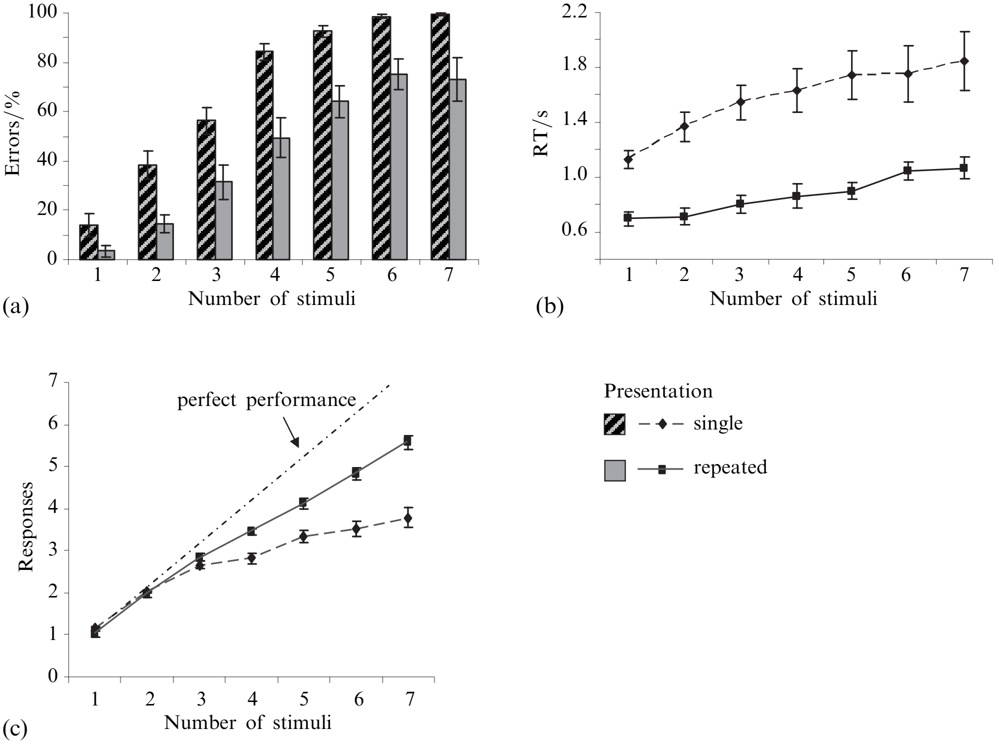

Figure 4. (a) Mean error rates in experiment 2 as a function of the number of tactors activated in the single-presentation and repeated-presentation conditions. (b) Mean RTs in experiment 2 as a function of the number of tactors activated in the single-presentation and repeated-presentation conditions. Note that RTs were measured from the offset of tactile stimulation. (c) Mean number of tactors reported by participants in experiment 2 as a function of the number of tactors activated in the single-presentation and repeated-presentation conditions. Error bars represent ±1 SEM.

An analysis of the error data revealed a significant main effect of numerosity ($F_{6,54} = 120.72$, $p < 0.0001$), block ($F_{1,9} = 66.08$, $p < 0.0001$), and an interaction between the numerosity and block factors ($F_{6,54} = 2.32$, $p = 0.045$). Error rates in the single-presentation block ($M = 69\%$) were higher than in the repeated-presentation block ($M = 44\%$), and increased with the number of stimuli presented for both block types (see figure 4a). An exploration of the interaction with an a posteriori Scheffé test (eg Scheffé 1959) revealed a significant difference between the single-presentation and repeated-presentation conditions when 2 ($p = 0.056$), 3, 4, 5, 6 ($p = 0.06$), or 7 tactors were activated (all ps < 0.01 unless stated otherwise), highlighting how significant differences in performance between the single-presentation and repeated-presentation blocks were observed whenever more than one stimulus was presented.

A similar analysis of the RT data revealed a significant main effect of numerosity ($F_{6,54} = 33.28$, $p < 0.001$), block ($F_{1,9} = 24.09$, $p < 0.0001$), and a significant interaction between these two factors ($F_{6,54} = 3.09$, $p = 0.011$). RTs in the single-presentation block ($M = 1570$ ms) were significantly slower than in the repeated-presentation block ($M = 860$ ms; though remember that RTs were calculated from stimulus offset). RTs in both blocks increased as the number of tactors activated increased (see figure 4b). An exploration of the interaction with a Scheffé test revealed a significant difference between the single-presentation and repeated-presentation conditions whenever more than 3 tactors were activated ($p < 0.05$ for all comparisons), again highlighting that the difference in performance between the single-presentation and repeated-presentation blocks increased as the number of vibrotactile stimuli presented increased.

An analysis of the mean response data revealed significant main effects of numerosity ($F_{6,54} = 296.61$, $p < 0.0001$) and block ($F_{1,9} = 68.90$, $p < 0.0001$), and a significant interaction between these two factors ($F_{6,54} = 38.27$, $p < 0.0001$). The mean value of the responses given by participants was lower in the single-presentation block ($M = 2.76$) than in the repeated-presentation block ($M = 3.39$). The numerical value of participants' responses also increased with the number of tactors activated for both block types (see figure 4c). An exploration of the interaction with a Scheffé test revealed a significant difference between the single-presentation and repeated-presentation conditions whenever 4 or more tactors were activated (all comparisons $p < 0.01$). Again, this interaction highlights how larger differences in performance (between the single-presentation and repeated-presentation blocks) were reported as the number of tactile stimuli presented increased.

Table 1 shows the confusion matrices for both the single-presentation and repeated-presentation blocks. The entries in the main diagonal cells (highlighted) represent the number of trials in which participants correctly enumerated the number of tactors presented. Visual inspection of the corresponding cells along the main diagonal in tables

Table 1. Confusion matrices for (a) the single-presentation and (b) the repeated-presentation conditions in experiment 2 highlighting the number of times participants made each response (1 to 7) when a given number of tactors was activated (note that the theoretical maximum for each cell is 350).

Number of tactors activated	Response						
	1	2	3	4	5	6	7
(a) Single presentation							
1	**301**	29	9	3	0	1	0
2	66	**216**	51	8	2	0	0
3	16	130	**153**	30	9	0	0
4	13	109	152	**55**	10	0	0
5	4	54	132	116	**26**	4	0
6	6	33	131	108	48	**5**	0
7	1	19	123	113	59	14	**2**
(b) Repeated presentation							
1	**334**	3	1	0	0	0	0
2	31	**296**	16	0	0	0	0
3	13	59	**239**	27	4	0	0
4	3	33	118	**172**	9	2	0
5	0	16	66	121	**126**	6	1
6	1	4	32	76	130	**92**	7
7	0	1	13	48	89	94	**95**

1a and 1b highlights the fact that participants responded correctly more often in the repeated-presentation condition than in the single-presentation condition. The entries off the main diagonal represent trials in which an erroneous response was made. More specifically, the cells in the triangle above the main diagonal represent the number of trials in which participants overestimated the number of tactors activated, and the cells in the triangle below the main diagonal represent the number of trials in which participants underestimated the number of tactors activated. A comparison of the cells in the triangles above and below the main diagonals within each table shows that participants tended to underestimate, rather than to overestimate, the number of tactors activated. Finally, the tables also show that the number of error trials in the cells closer to the main diagonal is generally larger than that in the cells further from the main diagonal, a trend that is more evident in the repeated-presentation block (table 1b) than in the single-presentation block (where participants seem to report that 3 or 4 sites were stimulated whenever the number of stimuli presented exceeded 2; see table 1a). This pattern of results suggests a gradual degradation in the accuracy of participants' responses in the sense that they were more likely to misjudge the number of tactors activated by 1 than by 2, etc. That is, the participants were not guessing or responding randomly when they were incorrect; instead, their responses were more likely to be close to the actual number of tactors activated.

Table 2 shows the total number of errors for each of the possible combinations of stimuli presented as a function of the number of tactors activated. Visual inspection of the table highlights the fact that performance was fairly uniform no matter which specific combination of tactors was activated on any given trial. These results may also help to rule out an interpretation of our results in terms of low-level sensory

Table 2. Number of errors (E) for each combination of activated tactors in (a) the single-presentation and (b) repeated-presentation blocks of experiment 2. Each pair of columns represents, for each number of tactors activated (1 to 7), their identity (ID; eg '1' = tactor 1 activated; '2' = tactor 2 activated; '12' = tactors 1 and 2 both activated, etc; see figure 2 for the corresponding position of each tactor on the body surface), and the number of errors (E) for all participants. Note that when all 7 tactors were activated only one stimulus configuration was possible. The number of errors was then 329 in the single-presentation block and 245 in the repeated-presentation block.

Number of tactors activated											
1	2	3	4	5	6						
ID	E	ID	E	ID	E	ID	E	ID	E	ID	E
(a) Single presentation											
1	3	**23**	9	**134**	27	**1235**	43	**12345**	45	**123456**	47
2	3	**26**	32	**135**	28	**1236**	45	**12356**	44	**123457**	49
3	7	**27**	15	**167**	30	**1256**	40	**12367**	45	**123467**	45
4	4	**35**	14	**235**	20	**1456**	37	**13456**	44	**123567**	46
5	5	**37**	22	**236**	24	**1567**	35	**13567**	43	**124567**	46
6	4	**45**	15	**237**	28	**2345**	37	**23457**	45	**134567**	47
7	16	**56**	20	**356**	28	**3467**	47	**23467**	44	**234567**	46
(b) Repeated presentation											
1	1	**23**	2	**134**	17	**1235**	30	**12345**	26	**123456**	34
2	1	**26**	14	**135**	12	**1236**	25	**12356**	31	**123457**	30
3	0	**27**	14	**167**	9	**1256**	17	**12367**	29	**123467**	35
4	0	**35**	2	**235**	13	**1456**	19	**13456**	27	**123567**	33
5	2	**37**	8	**236**	17	**1567**	23	**13567**	25	**124567**	29
6	0	**45**	3	**237**	15	**2345**	23	**23457**	39	**134567**	40
7	0	**56**	4	**356**	20	**3467**	28	**23467**	29	**234567**	39

interactions (such as interstimulus masking or summation). Masking and summation effects would have been expected to result in different levels of performance between the different tactor combinations and, in particular, worse performance for stimulus combinations where the tactors were placed close together (such as tactors 4 and 5) than for those where the tactors were far apart (such as tactors 2 and 6).

3.3 *Discussion*

The results of experiment 2 are consistent with those reported in experiment 1, again demonstrating the absence of any apparent subitising effect on tactile numerosity judgments. This failure to demonstrate a subitising effect occurred even when the stimuli were repeatedly presented over a period of 5 s in the repeated-presentation block, arguing against low-level sensory interactions (eg interstimulus masking or summation effects) being the sole factor responsible for poor performance as the number of stimuli presented was increased. Participants generally responded more rapidly and made fewer errors in the repeated-presentation block than in the single-presentation block. This finding presumably reflects the fact that the participants had more time (5 s) to shift their attention between different body locations in the repeated-presentation block than in the single-presentation block, where the stimuli were only presented for 200 ms (cf Lakatos and Shepard 1997).

It should be noted that all of the participants in experiment 2 completed the single-presentation block of trials before the repeated-presentation block. It could therefore be argued that the better performance reported in the repeated-presentation block might simply reflect a practice effect. In order to assess this possibility, two separate statistical analyses were performed, comparing the first and second half of trials in each experimental block. These analyses failed to reveal any significant effect of practice in either the single-presentation ($t_9 = -1.91$, ns) or repeated-presentation blocks ($t_9 = 0.28$, ns). Furthermore, contrary to the predictions based on the practice account, performance was quantitatively slightly better in the first than in the second half of each block.(1)

The intensity level for the vibrotactile stimuli was kept constant at the level set during the initial adjustment procedure for the duration of experiments 1 and 2. Given that the magnitude of vibrotactile sensation has been reported to increase linearly with the number of the stimuli presented (eg Cholewiak 1979; see also Craig 1966; Franzen 1969), it is conceivable that participants in experiments 1 and 2 may have based their numerosity judgments solely on the overall intensity of the vibrotactile stimulus array. In experiment 3, we explored the possible role of global stimulus intensity on participants' judgments by presenting different numbers of vibrotactile stimuli at different intensity levels. If participants' numerosity judgments in experiments 1 and 2 were based solely on the global perceived intensity of the stimulus display, modulating global stimulus intensity should dramatically affect participants' responses to the number of stimuli presented. Moreover, varying the level of perceived intensity should make it impossible for participants to discriminate between stimulus patterns at the same global intensity level but differing in the number of tactors activated.

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(1) Although practice does not appear to have affected performance in the present study, it is worth noting that both blind and sighted individuals need considerable practice in order to use the tactile vision substitution systems (TVSS) effectively (eg Bach-y-Rita 1972; Bach-y-Rita et al 1969). Moreover, skilled blind Braille readers can recognise Braille patterns under conditions of very brief presentation (eg Foulke 1979). Given these observations, it will be interesting for future research to investigate how tactile numerosity judgments with a whole body display might be affected by long-term practice, and whether blind people skilled in the use of TVSS-type displays will outperform sighted individuals.

4 Experiment 3

4.1 *Method*

4.1.1 *Participants.* Fourteen right-handed participants (six males and eight females) took part in this experiment as volunteers (mean age 18.9 years, range 18 – 20 years). All of the participants reported normal tactile perception. The experiment took approximately 40 min to complete and the participants received course credit in return for their participation.

4.1.2 *Apparatus, materials, design, and procedure.* The experimental setup and procedure were exactly the same as in experiment 1 with the following exceptions. After the initial adjustment of tactor intensity (baseline condition), two additional blocks of tactor intensity adjustment were also performed. In one block, the participants were asked to match the perceived intensity of each tactor with that of all 7 tactors presented simultaneously (7-tactor intensity matching condition). In the other block (2-tactor intensity matching condition), the participants had to match the perceived intensity of each tactor with the intensity of 2 tactors presented simultaneously at different body locations (tactors 1 and 3; note that this particular pairing of vibrators was not used in the main experiment). In order to perform this task, a first stimulus, consisting of all 7 tactors in one block and of 2 of the tactors in the other block, was presented for 200 ms. A second stimulus of the same duration, but consisting of the onset of only a single tactor, was presented 800 ms after the offset of the first stimulus. The first pattern was always presented at the baseline level of intensity. The participants were instructed to match the intensity of the second stimulus (single vibration) to the perceived intensity of the first stimulus (either all 7 or 2 vibrations) by asking the experimenter to increase or decrease the intensity of the second stimulus. The sequence was repeated until the participants were satisfied with their match (cf Craig 1966). The same procedure was repeated for each of the 7 tactors. The order of the two blocks of adjustment was counterbalanced across participants. The intensity levels for each tactor obtained with these procedures were then saved (see figure 5), and the main experimental session began.

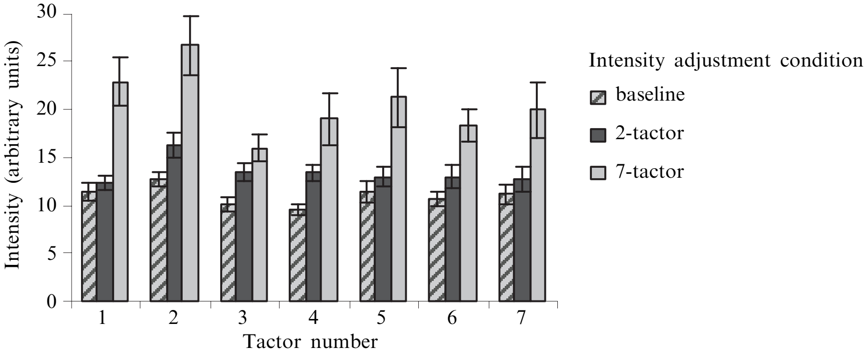

Figure 5. Intensity levels (in arbitrary units; cf Craig 1966) for each tactor as set by the participants in each adjustment block. Error bars represent ±1 SEM.

Three different conditions for the presentation of the vibrotactile stimuli were used: (i) the stimuli were presented at the baseline intensity; (ii) the stimuli were presented at the intensity levels obtained from the 7-tactor intensity matching procedure (ie each tactor was presented at an intensity equivalent to that of all 7 vibrators being activated at the baseline intensities); and (iii) the stimuli were presented at the intensity levels obtained from the 2-tactor intensity matching procedure (ie each tactor was presented at an intensity equivalent to that of 2 vibrators being activated at the baseline intensities). The three levels of intensity, and the order of presentation of the stimuli was completely randomised for each participant. Each number of stimuli was presented 28 times for each level of intensity, giving rise to a total of 588 trials completed by each participant.

4.2 *Results*

Trials in which participants failed to give a response before the trial was terminated (less than 4% of trials overall) were not analysed. The mean RTs, percentages of errors, and the mean numerical responses are highlighted in figure 6. Each of the three response measures was submitted to a repeated-measures ANOVA with the factors of numerosity (7 levels) and intensity (ie baseline, and 2-tactor and 7-tactor intensity levels). The analysis of the error data revealed a significant main effect of numerosity ($F_{6,78} = 383.12$, $p < 0.0001$), intensity ($F_{2,26} = 37.5$, $p < 0.0001$), and an interaction between these two factors ($F_{12,156} = 4.08$, $p < 0.005$). The analysis of the main effect of intensity was further analysed by submitting the data to paired-sample *t*-tests with Bonferroni correction. This analysis revealed significant differences between all of the intensity conditions (all *p*s < 0.005), showing that participants made fewer errors as the intensity of the vibrators was increased (see figure 6a). The interaction between numerosity and intensity was analysed with seven separate ANOVAs (one for each number of tactors activated) with the factor of intensity. The results are summarised in table 3, and show a significant effect of the intensity (ie lower error rates at higher stimulus intensity levels) when between 3 and 6 tactors were activated.

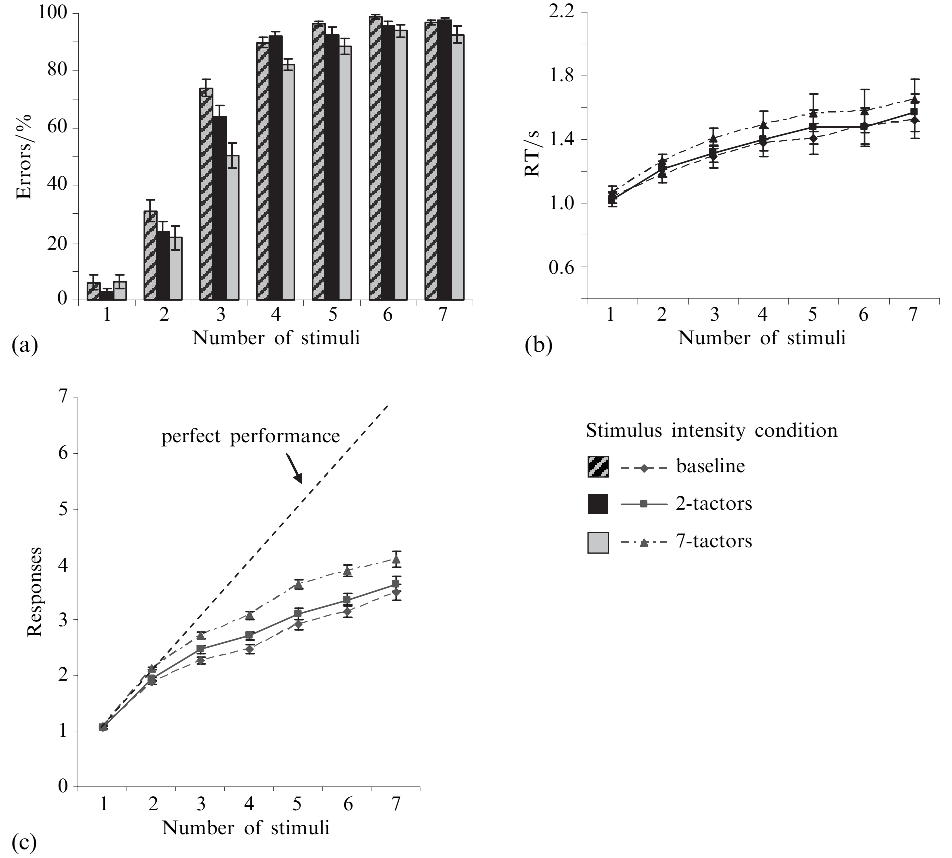

Figure 6. (a) Mean error rates in experiment 3 as a function of the number of tactors activated in the three intensity conditions. (b) Mean RTs in experiment 3 as a function of the number of tactors activated in the three intensity conditions. (c) Mean number of tactors reported by participants in experiment 3 as a function of the number of tactors activated in the three intensity conditions. Error bars represent ±1 SEM.

Table 3. Degrees of freedom, F values, and levels of significance (p) for the separate ANOVA on the error and response data, conducted on each number of stimuli presented. Bold p values indicate a significant effect of the level of intensity of the stimuli presented.

Number of stimuli	Degrees of freedom	Error data		Response data	
		F	p	F	p
1	2, 18	2.70	0.09	0.12	0.88
2	2, 18	3.17	0.06	8.13	**0.00**
3	2, 18	8.76	**0.00**	8.13	**0.00**
4	2, 18	7.62	**0.00**	5.50	**0.01**
5	2, 18	4.87	**0.02**	11.77	**0.00**
6	2, 18	4.81	**0.02**	7.78	**0.00**
7	2, 18	2.11	0.14	5.54	**0.01**

The analysis of the RT data revealed a significant main effect of numerosity ($F_{6,78} = 17.76$, $p < 0.0001$), with response latencies increasing as the number of tactors activated increased. The main effect of intensity was also significant ($F_{2,26} = 12.8$, $p < 0.0001$), with response latencies increasing as the level of stimulus intensity increased. The interaction between numerosity and intensity was not significant ($F_{12,156} = 1.04$, ns). The main effect of intensity was further analysed by submitting the data to paired-sample t-tests with Bonferroni correction. This analysis revealed significant differences between the baseline and the 7-tactor intensity conditions ($p < 0.005$), and between the 2-tactor and 7-tactor intensity conditions ($p < 0.05$) indicating that RTs were slower as the intensity of the vibrotactile stimuli was increased (see figure 6b). The increase in response latencies as the intensity increased seems to be directly related to the better performance in the higher-intensity conditions. As the intensity of the stimuli increased, performance became better (see figure 6a), and more stimuli were correctly perceived (ie there was less underestimation). Given that a linear relationship between the number of stimuli correctly perceived and RTs has been reported in previous visual numerosity research (eg Atkinson et al 1976a; Jevons 1871; Kaufman et al 1949; Saltzman and Garner 1948; Sathian et al 1999; Weiss 1965; and see also the results of experiments 1 and 2) one would expect RT to increase as more stimuli are processed.

The analysis of the response data revealed a significant main effect of numerosity ($F_{6,78} = 227.7$, $p < 0.0001$), intensity ($F_{2,26} = 15.5$, $p < 0.0001$), and an interaction between these two factors ($F_{12,156} = 8.09$, $p < 0.0001$). The main effect of intensity was further analysed by submitting the data to paired-sample t-tests with Bonferroni correction. This analysis revealed significant differences between all pairs of intensity corrections (all ps < 0.005), showing that participants gave higher responses as the intensity of the vibrotactile stimuli was increased (see figure 6c). The interaction between numerosity and intensity was analysed with seven separate ANOVAs (one for each number of tactors activated) with the factor of intensity (baseline, two-tactors, seven-tactors). The results are summarised in table 3, and show a significant increase in the mean value of the responses given by participants when between 2 and 7 tactors were activated. The interaction between numerosity and intensity was further analysed with three separate ANOVAs (one for each level of the intensity factor) with the factor of numerosity (1 – 7 tactors activated). These analyses revealed a significant effect of numerosity for each level of intensity (all $F_{6,78} > 138$; all ps < 0.0001), with participants' numerical responses increasing as the number of tactors activated increased for each level of stimulus intensity.

The numerical responses given by the participants to various different patterns of stimulation that shared the same overall level of perceived intensity (ie 1 tactor presented at the 2-tactors matched intensity level versus 2 tactors presented at the baseline intensity level; 2 tactors each presented at the 2-tactors matched intensity level versus 4 tactors presented at the baseline intensity level; or 3 tactors each presented at the 2-tactors matched intensity level versus 6 tactors presented at the baseline intensity level) were analysed by paired-sample t-tests. The analysis revealed significant differences for all three comparisons (all ps < 0.001; see figure 7). Overall, numerosity judgments were numerically higher for stimulus arrays with a greater number of tactors activated, despite the fact that the overall level of intensity was matched.

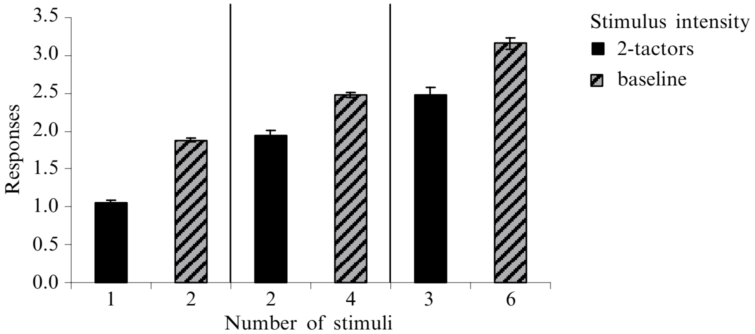

Figure 7. Mean numerical responses in experiment 3 as a function of the number of tactors activated in the baseline and two-tactors intensity conditions. Each of the three panels shows the effect of changes in numerosity on participants' numerical responses for pairs of conditions where the overall intensity of the vibrotactile displays was matched. Error bars represent ±1 SEM.

4.3 *Discussion*

The results of experiment 3 show that the global intensity of a spatially distributed tactile display had an effect on performance in our tactile numerosity judgment task. That is, the higher the perceived intensity of the stimuli the lower the number of errors made by the participants and the higher their RTs. However, the results of the comparison between the responses given to different numbers of activated tactors sharing the same level of perceived intensity clearly show that participants are not basing their responses only on the global intensity of the stimuli presented (see figure 7).

It is also worth noting that at the higher levels of perceived intensity (ie when each tactor was set at the 7-tactor matched intensity level) performance was still far below the levels reported in the repeated-presentation condition of experiment 2 (see figure 4a and figure 6a). This observation helps to strengthen the attentional interpretation of the results of experiment 2. That is, participants' performance improves significantly only when sufficient time is given to sequentially scan each body position moving the focus of attention across the body surface.

5 General discussion

The results of the three experiments reported here demonstrate that people are to some extent able to discriminate between different numbers of tactile stimuli when multiple tactors are activated simultaneously across the body surface. RTs and error rates for tactile enumeration judgments were linearly related to the number of tactors (1 – 7) activated in all three experiments. The error data from experiment 1 indicated that performance was poor (although error rates were mostly below the 85.7% chance level for erroneous responses) when more than 2 tactors were activated (see figure 3).

At first glance, the poor performance reported in experiment 1 might be interpreted as an inability of people to process simultaneously presented vibrotactile stimuli across the body surface in parallel. However, visual inspection of the mean responses given by participants in experiments 1 – 3 (see figures 3b, 4c, and 6c, respectively) reveals that participants' responses were linearly related to the number of tactors activated. When more than 2 tactors were activated, participants did not simply respond randomly, but, instead, were able to perceive a difference in the overall pattern (or amount) of stimulation (see also table 1). Although the accuracy of participants' responses decreased as the number of tactors activated was increased, their ability to discriminate patterns with more stimuli from those with less remained intact. This result was confirmed by means of a comparison between the single-presentation and repeated-presentation blocks in experiment 2, where the error rate was also reduced for conditions where larger numbers of tactors (5 or more) were activated.

There was no obvious sign of any discontinuity in the slopes of the RT or error data in any of the three experiments. Participants' performance appeared to be linearly related to the number of tactors activated on the body surface (ie as the number of tactors activated increased, RTs and error rates increased). Interestingly, a similar pattern of results has been reported previously in temporal numerosity judgments studies in which participants had to try and count the number of stimuli presented sequentially to a given body site (the fingers; eg Lechelt 1974, 1975). Lechelt (1974) reported that temporal numerosity judgments were linearly related to the number of stimuli presented, and that the slope of the function fitting the data was influenced by the rate of stimulus presentation (ie with performance decreasing as the rate of presentation increased above 12 stimuli s^{-1}). Lechelt's results together with the results reported in the present study both highlight the presence of important limitations in the processing of simultaneously presented tactile information. However, it is important to note that the similarity in performance reported in these two studies need not be interpreted in terms of a similar underlying cognitive mechanism. In particular, limitations in the processing of the information related to the spatial position of the stimuli may be a crucial factor in limiting the accuracy of spatial numerosity judgments (ie participants need to know that the stimuli are coming from different body/spatial positions in order to count them), but not in the studies of temporal numerosity judgments. The relationship between the cognitive mechanisms underlying temporal versus spatial numerosity judgments (and, in particular, the role played by spatial versus non-spatial selective attention, respectively; cf Hillstrom et al 2002) should be explored further in future research.

The results of experiment 3, showing a significant difference between judgments of the numerosity of different numbers of stimuli having the same overall level of global intensity, help us to rule out global intensity as the sole factor modulating performance in experiments 1 and 2. However, it is important to highlight the fact that variations in the intensity of the stimuli presented in experiment 3 still affected performance, reducing the number of errors when the tactors are activated at higher levels of intensity (see figure 6a).

The results of the present study bear comparison with those of Ginsburg and Pringle (1988) who also reported a linear relationship between the number of tactile stimuli presented (10 – 36) and the responses given by their participants. In particular, they reported that the participants' overall estimates (E) increased monotonically as a function of the number of stimuli presented (S), fitting the following equation: $E = 0.76S + 1.3$ (see table 4, for the equations fitting the data of our experiments 1 – 3). However, one of the main differences between Ginsburg and Pringle's experiment and our own is that the participants in their study were requested to scan the stimuli with one hand, using an active touch procedure (ie a kind of overt attentional orienting), whereas in our study, by contrast, only passive tactile perception was involved. If any kind of scanning was used by participants in the present study, this could only have been a kind of covert 'attentional' scanning (ie related to the covert shifting of attention between different vibrator locations on the body surface). Indeed, in the repeated-presentation block of experiment 2, participants could presumably have directed their

Table 4. Best fitting equations for the data in each condition of experiments 1–3. $E =$ participants' estimation of the number of stimuli presented; $N =$ number of tactors actually activated.

Experiment	Condition	Equation
1		$E = 0.54N + 0.76$
2	Single presentation	$E = 0.41N + 1.11$
	Repeated presentation	$E = 0.73N + 0.43$
3	baseline	$E = 0.37N + 0.96$
	two-tactors	$E = 0.40N + 1.00$
	seven-tactors	$E = 0.48N + 1.02$

attention sequentially to several different body sites during the 5 s of stimulus presentation (cf Lakatos and Shepard 1997). This may have allowed participants enough time to sequentially count the number of stimuli presented. This could perhaps help to explain the better performance reported in the repeated-presentation condition (where more time for attentional scanning was allowed) than in the single-presentation condition of experiment 2.

Franzen et al (1970) presented tactile stimuli on one or two fingers simultaneously and reported that participants were not able to attend to more than one finger at any given time. By contrast, the results of many other studies would appear to suggest that people can attend to more than one stimulus location at a given time, but that dividing attention results in some loss of performance in processing spatial patterns in terms of an increase in the number of errors (eg Craig 1966, 1985; Geldard and Sherrick 1965; Gilson 1969). The results of the present study show that participants can effectively perceive an increasing number of activated tactors when sufficient time is given to switch their attention between different body locations (eg Geldard and Sherrick 1965). Under conditions where multiple tactile stimuli are only briefly presented across the body surface there appears to be a profound attentional limitation in processing information concerning the number of tactors activated.

The data reported here appear to contrast with the results of the majority of previous studies of visual and auditory numerosity judgments reviewed earlier, in which a robust discontinuity was reported to occur between responses to more versus less than 4 stimuli. One possible interpretation of this difference is that subitising is restricted to the enumeration of small numbers of visual and auditory stimuli, and that it does not occur for stimuli presented in the tactile modality. In vision there seems to be a limit of 4 pre-attentively processed items that can be selected at any one time (eg Trick and Pylyshyn 1993). By contrast, tactile perception, given its better temporal discrimination (at least as compared with vision; eg Geldard 1960; Lechelt 1975), might be more efficient in operating 'serially' (eg Bach-y-Rita et al 1969; cf Lechelt 1975). The result of this difference in information processing is that very few locations (one or two) can be analysed at the same time by touch without a significant performance decrement being reported (cf Craig 1985).

However, one might also question whether subitising and counting are really two independent and separate phenomena as suggested by the majority of researchers (eg Trick and Pylyshyn 1994). It is perhaps worth noting that some researchers have argued against the separability of the two processes at both the cognitive and neural levels (Balakrishnan and Ashby 1991, 1992; Piazza et al 2002), and alternative suggestions have been made concerning the underlying nature of the counting and subitising phenomena. For instance, Balakrishnan and Ashby (1992) analysed a wide range of enumeration data and were unable to show any statistical evidence for a discontinuity in response latencies between subitising and counting. On the basis of their analysis, Balakrishnan and Ashby concluded that the two processes are not different in nature, but simply reflect a continuum along a scale of increasing task difficulty (ie 'mental effort'). Support for a quantitative rather than qualitative difference between the two types of processing, at least at a neurological level, has been reported on the basis of brain-imaging studies. Piazza et al reported overlapping brain activation in the extrastriate middle occipital and intraparietal areas for counting and subitising in their PET study suggesting (according to the authors) that a common neural network may be involved in the two processes.

Certain experimental manipulations have been demonstrated to reduce the difference between subitising and counting quite dramatically in terms of errors and RTs. For example, Atkinson et al (1976a) reported that increasing the spatial frequency of stimuli from 2 to 22 cycles deg^{-1} in a visual numerosity judgment task resulted in a change in the slope of both the RT and accuracy data. Increasing the spatial frequency of the items eventually eliminated the discontinuity point distinguishing subitising from counting, thus giving rise to a continuous linear function. Moreover, a recent psychophysical study by Daini et al (2002), who used a contrast detection paradigm with visual stimuli, failed to report any difference between participants' judgments in the subitising and post-subitising ranges. Taken together, such results suggest that the emergence of a difference in participants' performance between enumeration performance in the subsitising and counting ranges may to some extent be dependent on the experimental task used, and may not reflect a truly cognitive and/or neural distinction between two separate processes.

The results of the present study therefore seem to support the view that the enumeration of tactile stimuli may not involve two different processes (counting and subitising), at least at a behavioural level, but might instead represent a continuum of difficulty (probably in terms of the attentional resources necessary to perform the task). Recently, Joseph et al (1997) demonstrated that the detection of a simple visual feature, such as orientation (which is commonly thought to be processed at a pre-attentive level; eg Treisman 1985), is severely impaired when participants have to perform a secondary attention-demanding task at the same time. The authors argued against the presence of some attention-free form of visual processing, and instead suggested that a participant's performance in any task may be related to the availability of limited attentional resources. On the basis of these data, as well as the data reported in the present study, one might also wonder if subitising should be considered not in terms of attention-free processing, but as the lower part of a continuum expressed in terms of resources necessary to perform the task (cf Braun 1998).

Taken together, the results of the experiments reported here demonstrate that information can to some extent be conveyed by touch in parallel with use of the body as a receptor surface. However, our results clearly show that the correctness of tactile numerosity judgments decreases dramatically with relatively modest increases in the number of tactors activated. Participants appear able to estimate differences in the number of tactors composing the pattern delivered on the body, but less able to perceive information about the actual quantity correctly (ie the participants knew that the number of tactors presented is different between 1 and 7, or between 2 and 5, but they could not identify correctly the number of tactors actually activated). This might represent an analogous behaviour to that reported in visual numerosity judgments experiments. Indeed, it has been demonstrated that when the number of visual stimuli presented exceeds a certain value, and when insufficient time is available for observers to accurately count all the items presented, participants stop counting and start using a less accurate 'estimation' procedure instead (see Dehane 1992). The global intensity of the stimulus array presented might be one of the factors influencing estimates of numerosity when cognitive/attentional limitations are exceeded.

Other factors, such as the effect of different combinations of stimuli across the body surface (see table 2); the single presentation versus repeated presentation of stimuli, and variations in the intensity of stimulation that can contribute to improve the processing of information in parallel over the body surface, should be analysed in future research. As well as being of theoretical interest, the results reported here may be of interest for the development of human – machine tactile and multisensory interfaces (eg van Erp 2000; van Erp and van Veen 2004; Ho et al 2005; Rochlis and Newman 2000; Rupert 2000; Sorkin 1987; Spence and Driver 1999). Research now shows that tactile stimuli can be used to convey information reliably under conditions of high gravitational load when visual information is severely degraded (van Veen and van Erp 2000). Tactile stimulators arrayed over the body surface have also been used successfully to resolve spatial disorientation in aviation environments (eg Rupert 2000), to convey aircraft position and motion information to pilots (eg Rupert et al 1994; van Veen and van Erp 2003), to support orientation awareness of astronauts in a micro-gravity environment (eg van Erp and van Veen 2003), and to cue driver attention in cars (eg van Erp and van Veen 2001, 2004; Ho et al 2005). However, although there has been a rapid growth of interest in the body surface as an alternative means of conveying information to many different kinds of interface operators, several fundamental questions associated with the presentation of multiple tactile stimuli have yet to be addressed. These include questions related to the kind of information that is best conveyed by touch, how many sources of tactile information can be tracked in parallel, and how many locations tactile attention can be directed toward at any one time (cf Lakatos and Shepard 1997; Spence 2002). Answering the question how many stimuli can be perceived on the body surface at any one time may therefore not only inform our understanding of tactile attention and information processing, but also provide constraints for the development of tactile interfaces for human operators (eg Spence and Driver 1999).

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