Perception, 2008, volume 37, pages 782 – 800

doi:10.1068/p5767

Can tactile stimuli be subitised? An unresolved controversy within the literature on numerosity judgments

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Received 14 February 2007, in revised form 18 July 2007; published online 1 May 2008

Abstract. There is a growing interest in the question whether the phenomenon of subitising (fast and accurate detection of fewer than 4 – 5 stimuli presented simultaneously), widely thought to affect numerosity judgments in vision, can also affect the processing of tactile stimuli. In a recent study, in which multiple tactile stimuli were simultaneously presented across the body surface, Gallace et al (2006 *Perception* **35** 247 – 266) concluded that tactile stimuli cannot be subitised. By contrast, Riggs et al (2006 *Psychological Science* **17** 271 – 275), who presented tactile stimuli to participants' fingertips, came to precisely the opposite conclusion, arguing instead that subitising does occur in touch. Here, we re-analyse the data from both studies using more powerful statistical procedures. We show that Riggs et al's error data do not offer strong support for the subitising account and, what is more, Gallace et al's data are not entirely compatible with a linear model account of numerosity judgments in humans either. We then report an experiment in which we compare numerosity judgments for stimuli presented on the fingertips with those for stimuli presented on the rest of the body surface. The results show no major differences between the fingers and the rest of the body, and an absence of subitising in either condition. On the basis of these observations, we discuss whether the purported existence of subitisation in touch reflects a genuine cognitive phenomenon, or whether, instead, it may reflect a bias in the interpretation of the particular psychometric functions that happen to have been chosen by researchers to fit their data.

1 Introduction

The study of people's ability to make visual numerosity judgments goes back more than a century (eg Jevons 1871; Warren 1897). By now, many researchers have reported that there is a difference in both the accuracy and latency of people's behavioural responses when enumerating small versus large numbers of visual stimuli (eg Atkinson et al 1976a; Trick and Pylyshyn 1993, 1994; Weiss 1965). Specifically, when the number of items presented is small (typically between 1 and 4 stimuli) they appear to be processed very rapidly and almost free from errors (eg Atkinson et al 1976a). By contrast, increasing the number of items presented above 4 typically produces a large increase in both average response latencies and error rates, often giving rise to a discontinuity in the slope of the response latency and error functions. Such results have been interpreted by many authors as providing evidence for the existence of two qualitatively different enumeration processes: 'subitising', specialised for small numbers, and 'counting', specialised for larger numbers of items (eg Kaufman et al 1949; Mandler and Shebo 1982; Peterson and Simon 2000; Trick and Pylyshyn 1993). Subitising has been described as fast, accurate, and pre-attentive, whereas counting tends to be slower, more error-prone, and more attention-demanding.

Given the importance that has been attributed to the phenomenon of subitising in terms of explaining (at least in part) the neural and cognitive mechanisms underlying the selection of information, spatial processing, and the access of information to consciousness (eg see Jevons 1871; Pylyshyn 1989; Sathian et al 1999; VanRullen and

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Koch 2003a, 2003b; cf Gallace and Spence 2008), it is somewhat surprising to see how few researchers have attempted to investigate the limitations in people's ability to count stimuli presented outside of the visual modality (such as, for example, for stimuli presented in the auditory or tactile modalities; see Alluisi et al 1965; Gert and Joos 1979; Hill 1971; Kashino and Hirahara 1996; Lechelt 1974, 1975; Monty 1962; Taubman 1950; White et al 1953; see also Gallace et al 2007a). The results of numerosity studies have been used to highlight the limitations affecting our awareness of simultaneously presented stimuli (see Gallace and Spence 2008). While the presence of subitising in vision appears to suggest that people's awareness of events is limited to 3–4 stimuli presented at the same time, the same limitation does not necessarily apply to other sensory modalities. Moreover, the question of how much information can enter awareness at any one time is not only of theoretical but also of applied importance, given the increasing number of attempts to develop a tactile interface to present information to human–machine operators (see Gallace et al 2007b, for a recent review).

Two studies have recently been published in which people's ability to counter various numbers of simultaneously presented vibrotactile stimuli has been investigated (Gallace et al 2006; Riggs et al 2006). Rather surprisingly, however, while Gallace et al concluded that subitising "does not occur for stimuli presented in the tactile modality" (page 262), Riggs et al came to exactly the opposite conclusion, suggesting, instead, that subitising "is not restricted to visual perception, but also extends to tactile perception" (page 271). These two studies of tactile numerosity judgments differ in terms of where the stimuli were presented: Gallace et al presented vibrotactile stimuli (1 to 7) to a variety of different locations across their participants' body surface, while Riggs et al presented tactile stimuli (1 to 10) to their participants' fingertips instead [note that both studies used passive simultaneous stimulus presentation rather than active scanning procedures; cf Ginsburg and Pringle (1988) for results obtained with haptic sequential estimation of larger numbers of tactile stimuli]. It might be possible, therefore, that any putative difference between the results of the two studies could be related to the fact that most people are more practiced at discriminating tactile stimuli presented to their hands (as in Riggs et al's study) than using other parts of their body surface (as the participants in Gallace et al's study). Indeed, it is well-known that a larger proportion of the somatosensory cortex is given over to the representation of the hands than of other parts of the body, given their relative surface area (eg Nakayama et al 1998; Narici et al 1991; Penfield 1950). Note that this difference might also help to explain the large overall difference in error rates reported in the two studies (see figure 1). Participants made far more errors in Gallace et al's study, where the stimuli were presented on the body surface, than did participants in Riggs et al's study, where the stimuli were presented on the fingertips.

It is, however, important to note that any theoretical interpretation of the differences between diverging scientific findings assumes that the actual 'results' of the studies in question differ in certain fundamental respects. However, this may not be the case here: indeed, the results of the two studies might actually in both cases belong to the same family of performance curves (such as, for example, 'exponential' functions), and therefore perhaps be related to the functioning of similar processing mechanisms. Note, however, that despite this possible (and yet unexplored) similarity between the results of the two studies, the data were actually fitted with different psychometric functions. In particular, while Gallace et al (2006) fitted their response time (RT) data with a single linear function ($\mathrm{RT} = 144N + 906$; correlation coefficient $r = 0.99$, where N represents the number of stimuli in the display), Riggs et al plotted two separate linear functions by splitting (on the basis of the results reported in certain previous visual studies) their latency data into two distinct numerosity ranges ($\mathrm{RT} = 270N + 490$, $r = 0.99$, for 1 to 3 tactile stimuli and $\mathrm{RT} = 627N - 668$, $r = 0.99$,

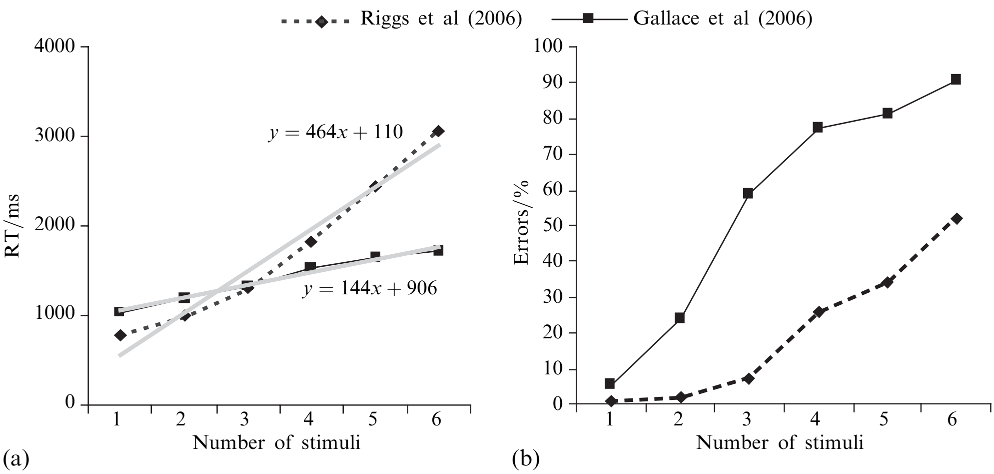

Figure 1. Performance of participants in Riggs et al's (2006) and Gallace et al's (2006) tactile numerosity judgment studies as a function of the number of stimuli presented in the display: (a) mean RTs—the best-fitting functions (light grey lines) with their equations are also represented for both data sets; (b) the error data from the two studies.

for 4 to 6 tactile stimuli, respectively. Note that Riggs et al did not analyse the numerosity data when 7–10 stimuli were presented owing to the particular response strategy apparently used by their participants, which was to start counting the unstimulated fingers.).

The key point to note here is that the authors of both studies failed to provide convincing support for their claims regarding the presence or absence of subitising in the tactile modality. Both approaches might therefore be incomplete in terms of answering the question whether or not two separate forms of processing (subitising and counting) are involved in numerosity judgments for tactile stimuli. Specifically, Riggs et al (2006) plotted two separate functions, splitting their data on the basis of the results of previous visual research (a method that has also frequently been used in the visual literature; eg Chi and Klahr 1975; Svenson and Sjöberg 1978). However, such a method is not based on statistical evidence (regarding a discontinuity) provided by the data set itself but rather on the arbitrary choices made by individual researchers on the basis of previously reported evidence (the statistical validity of which has actually been questioned elsewhere; eg Balakrishnan and Ashby 1992).(1)

Moreover, using this method (ie splitting the data into two ranges and fitting two different curves), Riggs et al (2006) actually failed to fit a bilinear function to their data. Indeed, in order to show that any data set is fitted by a bilinear function one should perform a piecewise linear regression analysis (eg Neter et al 1990, pages 474–477). Such a procedure allows one to fit functions that change their slope at a specific point (the limit of the subitising range in the present case). Moreover, while the precise limit of the subitising range appears to be controversial with different researchers suggesting that subitising occurs for up to 3 (eg Atkinson et al 1976a; Chi and Klahr 1975), 4 (eg Klahr and Wallace 1976; Trick and Pylyshyn 1994), or even 5 stimuli (see Simons

(1) One possible means of statistically defining the limit of subitising is to perform a series of planned comparisons between each pair of consecutive numerosities (ie comparing the numerosity equal to n with the numerosity equal to $n + 1$ in the response times and/or in the error data). By means of such a procedure, the subitising limit could be statistically defined as the smallest numerosity for which the comparison is significant. Applying this procedure to the original data set (Riggs et al 2006) the minimum numerosity that can be used to statistically determine a discontinuity in the data set is '1' for both RTs ($t_{15} = -5.86$, $p < 0.00001$, two-tailed) and error rates ($t_{15} = -2.55$, $p < 0.05$, two-tailed). By itself, this result would undermine the very possibility of splitting the data at a numerosity equal to 3 (before fitting the data) as reported by Riggs et al (2006).

and Langheinrich 1982), Riggs et al analysed their data only for the case where the subitising limit was set at 3 stimuli.

Note also that Riggs et al (2006) reported a per-item increase within the subitising range of 270 ms, a result that is actually not particularly compatible with a subitising account of their data (for comparison, it should be noted that the per-item increase reported in the visual subitising literature does not exceed 40 – 100 ms at most for adult participants—Chi and Klahr 1975; Simons and Langheinrich 1982; Svenson and Sjöberg 1978; Trick and Pylyshyn 1994). Indeed, even smaller (200 ms) per-item increases than those reported by Riggs et al have been used elsewhere to reject the very possibility that participants were actually subitising the items presented (eg Butterworth 1999; Piazza et al 2002). Although Riggs et al seem to accept the claim that the presence of 'any' kind of discontinuity in the data set can actually be sufficient to support the distinction between counting and subitising (eg Trick and Pylyshyn 1994),(2) one should also consider whether or not this choice may undermine the very nature of the theorisation regarding subitisation itself.

Specifically, one of the central differences between counting and subitising has always been the fact that subitising is a pre-attentive process, whereas counting is an attention-demanding process (eg Cowan 2001, 2005; Kaufman et al 1949; Mandler and Shebo 1982; Peterson and Simon 2000; Trick and Pylyshyn 1993, 1994). Cowan (2001, 2005) even suggested that subitising may help to estimate the capacity limit of the focus of attention (that is, the number of stimuli that can be held within the focus of attention at any one time without shifting it). Therefore, if subitising is thought to be a pre-attentive process (ie a process that does not require any shift of attention), one might legitimately ask how a per-item increase of 270 ms [an interval that has been shown to be sufficient for a shift of tactile attention to occur; eg Lakatos and Shepard (1997); Spence and McGlone (2001)] may be considered as evidence for the presence of subitising in touch. This point alone would at least suggest a reconsideration of the nature of subitising in touch!

Finally, it is also important to note that Riggs et al (2006) presented their stimuli until a response was given by participants, once again using a procedure that is not entirely compatible with the concept of subitising reported in the earlier literature. [Note that the term 'subitising' is derived from the Latin word subitus—meaning 'sudden'—and captures the feeling of immediately knowing or 'apprehending'—James (1890/1950); see also Chi and Klahr (1975).] Therefore, one might question how the presentation of the stimuli "until a response is made" can be seen as being compatible with a lack of ocular movements or attention shift thought to be proper of the subitising concept.

On the other hand, one can also criticise Gallace et al's (2006) study on the grounds that they only analysed their data using a linear model (ie without also trying to plot alternative bilinear functions and therefore exploring other possible interpretations for their data). Finally, while both studies provided the r^2 values relative to their fittings (a measure of the percentage of variance that can be explained by a given model) they did not actually test for the degree of correspondence between the data that would have been expected on the basis of their models and the data that were actually observed (ie they did not provide a statistical measure of the goodness-of-fit of their data-fitting procedures). The same concerns also apply to the measure of the participants' error rates provided by the two studies. Therefore, in order to try to clarify these points, and, additionally, to determine whether either set of data provides a definitive answer to the question of whether subitising affects the processing of tactile stimuli, we re-analysed both sets of empirical data using similar statistical procedures.

(2) Although it is worth noting here that, in their study, Trick and Pylyshyn (1994, see page 80) report the classic 40 – 100 ms and 250 – 350 ms ranges as limits for the subitising and counting processes, respectively, and the 'shallow' slope of the function within the subitising range.

Linear, logarithmic, quadratic, exponential, sigmoid, power regression, and piecewise regression psychometric analyses (with pivot points at numerosities of 3 and 4) were performed on both Riggs et al's (2006) and Gallace et al's (2006) RT and error data (see Appendix, tables A1 and A2). The analysis of the goodness-of-fit by using a χ^2 merit function showed that the latencies predicted by linear, quadratic, power, and bilinear models with pivots at numerosities of 3 and 4 were not significantly different from those reported by Gallace et al. Note that, although the results predicted by the bilinear models were not significantly different from those obtained by Gallace et al, the slopes of the two parts of the curves between the pivot points in the data obtained by Gallace et al are not those expected on the basis of a subitising account. Indeed, the slope in the subitising range is steeper than the slope in the counting range (see Appendix, Table A1c), confirming the view that a classical dual-process model of numerical abilities cannot be used to account for the results of Gallace et al.

The analysis of the goodness-of-fit of the data also showed that the results predicted on the basis of quadratic and both bilinear models (with pivot points set at 3 and 4) were not significantly different from those obtained by Riggs et al (2006). This finding highlights the fact that at least two different models can be used to fit the data of Riggs et al. Note, however, that only the bilinear model is fully consistent with a classical dual-processing account (ie counting versus subitising) of numerical abilities. Moreover, although the bilinear model appears to fit Riggs et al's RT data correctly, this observation by itself does not provide sufficient evidence with which to come to any firm conclusions regarding the presence of two distinct forms of processing in tactile perception. Indeed, it is important to note that the per-item increase in RTs obtained within the subitising range reported by Riggs et al (270 ms/item) corresponds approximately to the time needed for a young adult (French speaker, as in the study by Riggs et al) to 'count' visual objects one by one while pointing at them with a finger (ie 215 – 266 ms; eg Camos et al 2001). This observation suggests the possibility that even within the subitising range, participants in the Riggs et al study may actually have been counting the number of stimuli presented rather than subitising them. Moreover, the 270 ms/item increase observed by Riggs et al for small numerosities (and the 253 ms/item and 371 ms/item predicted by the bilinear model with pivot points equal to 3 and 4, respectively) is an interval large enough to allow for attentional shifts between the tactile stimuli presented, offering further support for the claim that participants in the Riggs et al (2006) study were not subitising the items but likely shifting their attention serially amongst them. Therefore, although the analysis reported by Riggs et al was compatible with the presence of a discontinuity in the data set, this result, by itself, does not appear to be fully in agreement with a classic counting versus subitising account of numerosity judgments.

As far as the error data are concerned (see figure 1b; note that Riggs et al 2006, did not themselves attempt to fit any psychometric functions to their error data), it is interesting to note that both Gallace et al's (2006) and Riggs et al's data can be fitted, with only marginally different r^2 values, by using linear, logarithmic, quadratic, power, sigmoidal, exponential, and bilinear functions (see table A2). Most importantly, the analysis of the goodness-of-fit, by means of a χ^2 test, showed that the quadratic and bilinear models with pivot points at 3 and 4 best predicted Gallace et al's results (see Appendix, tables A2c and A2d). Note also that the results predicted by the linear model were found to be significantly different from those observed in the experimental group studied (suggesting that this model may not provide the most appropriate fit to the data). The goodness-of-fit analysis also showed that the results predicted on the basis of all of the models analysed were significantly different from those obtained by Riggs and his colleagues. It is therefore of relevance to note here that the bilinear model with a pivot point at a numerosity of 3 (the model suggested by Riggs et al as being the best in terms of representing their data, and predicted on the basis of certain previous visual studies—eg Atkinson et al 1976a) was actually not predictive of the results that they actually obtained.

The fact that many different ways of fitting the data are seemingly equally effective in predicting the results would therefore appear to suggest that any decision regarding the function that best fits the data emerging from studies of tactile numerosity judgments (and, as a consequence, any theoretical speculation regarding the cognitive mechanism underlying it) may be fairly arbitrary at present (rather than being fundamentally determined by the underlying nature of the data sets themselves). Indeed, depending on the specific model that the researcher decides to fit and test against the obtained results, dramatically different conclusions can actually be supported.

Therefore, on the basis of these observations regarding the empirical data reported by both Gallace et al (2006) and Riggs et al (2006), the possibility ought to be considered that the enumeration of tactile stimuli might not actually reflect two distinct and cognitively separable processes (subitising and counting) as suggested by Riggs et al (2006), but rather just the consequence of an interpretation bias arising from the particular way in which the psychophysical data happen to have been fitted. Interestingly, a similar argument runs through the earlier literature on visual enumeration judgments (eg Balakrishnan and Ashby 1991, 1992). In fact, when Balakrishnan and Ashby (1992) analysed a wide range of enumeration data, they were unable to show any statistical evidence for a discontinuity in response latencies between the subitising and counting ranges (note, however, that they were also unable to fit a log–linear model to the numerosity data that they analysed). This led the authors to conclude that the two processes are not different in nature, but simply reflect a continuum along a scale of increasing task difficulty ('mental effort'). Of course, the question of whether a single cognitive process underlies numerosity judgments may become even more complex when one starts to consider the enumeration of bimodal rather than unimodal displays (see Gallace et al 2007a; cf Loftin 2003).

It is also important to note here that the purported limit of subitising has also been shown to be modulated by practice. Specifically, Wolters et al (1987) demonstrated that after 5 days of practice involving the presentation of visual patterns composed of 4 to 18 dots, subitising occurred over the whole range of stimuli presented! This result was, however, only found when the patterns presented were constant across different trials and different days of testing, but not when they were generated randomly before each trial (in this latter case, subitising never developed). It therefore appears clear that, if present, any difference between the results obtained for the counting and subitising ranges in vision, and possibly also in touch, might solely be due to the demands of the tasks being performed by participants and to the experience that they may have with the patterns of stimuli presented, rather than to the functioning of two separate and/or independent processing systems. These latter observations would also suggest that extensive practice with specific patterns of tactile stimulation (and perhaps also the use of feedback regarding the correctness of participants' responses) might lead to an improvement of participants' performance in tactile numerosity judgment tasks and even to the appearance of a subitisation-like phenomenon.

However, before drawing any firm conclusions regarding the cognitive processing underlying tactile numerosity judgments, we should note that the present analysis also highlighted the fact that the results of Gallace et al (2006) were not predictable on the basis of a linear model (at least as far as their error data are concerned). This last observation might perhaps suggest that numerosity judgments in tactile perception are not even easily described by a unitary account. However, one should consider the fact that this failure to fit Gallace et al's data with a linear model is not due to a discontinuity between the subitising and counting range, but rather to a discontinuity in the post-subitising range. That is, increasing the number of stimuli resulted in performance reach ceiling level and therefore gave rise to a shallower distribution above a certain numerosity value. Note that this is exactly the opposite pattern of results than one would expect on the basis of a subitising account (where the shallow distribution is found in the first rather than second part of the data set). What is more, this pattern of results (the presence of a shallow distribution due to a ceiling effect at some point in the data set) is a frequent occurrence in most psychophysical studies (eg Pollack 1952; Stevens 1951, 1958; including those studies involving visual numerosity judgments, eg Balakrishnan and Ashby 1992) and cannot be avoided. Ultimately, what is interesting here is that the asymptote (perhaps corresponding to a shift between a serial counting procedure and an estimation procedure; eg Mandler and Shebo 1982) for tactile numerosity judgments seems to be obtained for lower numerosities than for visual numerosity judgments.

Our analyses also suggest that differences are present between the two sets of data. In particular, the error data of Gallace et al (2006) can be described by a linear function but those of Riggs et al cannot. As previously noted, these differences might be related to the locus of presentation of the stimuli in the two studies (fingers versus body). Indeed, most people are presumably more practiced at discriminating tactile stimuli using their hands than using other parts of their body surface. Finally, this difference might also be related to the proportion of the cortical surface involved in the representation of the stimuli presented [see Baron and Pelli (2006) for the report of a decrement in the accuracy of participants' visual numerosity judgments when stimuli are presented at the periphery of the visual field—an area represented in V1 less than the fovea—cf Gallace and Spence 2008].

In order to further investigate any possible difference in numerosity judgments for stimuli presented on the fingertips versus on the rest of the body surface, we conducted an experiment in which we compared the two conditions of stimulus presentation (fingertips versus body surface) within the same group of participants using exactly the same experimental setup. Moreover, in accordance with the extant visual literature, we used brief presentation of the stimuli (100 ms) in order to avoid ocular movements or attentional shifts.

2 Experiment

2.1 *Methods*

In one experimental condition, the stimuli were presented on the fingertips (we used the 8 fingers of both hands, excluding the thumbs), while in the other condition the stimuli were presented across the body surface (cf Auvray et al 2007; Gallace et al 2006, 2007a, 2008). The vibrotactile stimuli were presented by means of resonant-type tactors (Part No: VBW32, Audiological Engineering Corp., Somerville, MA, USA), with 1.6 cm × 2.4 cm vibrating surfaces. The vibrators were driven by means of a custom-built 9-channel amplifier circuit (Haptic Interface Laboratory, Purdue University, West Lafayette, IN, USA) that drove each tactor independently at 290 Hz (close to its resonant frequency).

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 with a similar intensity. This was achieved by asking participants to match the perceived intensity of the first tactor activated with that of each of the others. The amplification levels for the tactors were kept at these individually adjusted levels throughout. The tactors used to stimulate the body surface were placed on the participant's body on the top of his/her clothes by means of Velcro strip belts at the following locations: left wrist; midway between the elbow and the shoulder on the left arm; just above the right elbow; just below the left knee; just above the left ankle; midway between the ankle and knee on the right leg; on the waistline, to the left and right of the body midline (cf Gallace et al 2006; Geldard 1968; Geldard and Sherrick 1965; for similar locations of stimulus presentation). The tactors used to stimulate the fingertips were covered with a layer of foam and mounted directly on each of the participant's fingers by means of Velcro strip belts. The latter solution was adopted in order to prevent any transmission of vibration through solid surfaces where the tactors might have been mounted.

A maximum of 6 stimuli were presented at any one time in both conditions. The stimuli were presented for 100 ms, preceded by a 100 ms alerting tone. White noise was presented over closed ear headphones at 70 dB(A) to mask any sound made by the operation of the vibrotactile stimulators (cf Gallace et al 2006). The number of tactors activated on each trial for each condition varied randomly between 1 and 6. 15 stimuli were presented for each numerosity, giving rise to a total of 90 stimuli presented in each condition. The participants ($N = 11$, seven male and four female, mean age 27.6 years, range 26 – 36 years) were asked to vocally report, as accurately as possible, the number of stimuli they felt in each trial. They were also informed that the trial would be terminated if a response was not given within 6 s from the stimulus onset. The latencies of participants' responses were collected by means of a microphone (Pro-sound unidirectional dynamic YU33 600 Ω and 50 kΩ) connected to a custom-built voice key, while the numerical response values given by the participants were transcribed by the experimenter. The two conditions of stimulus presentation in the tactile modality were preceded by a control condition in which the participants had to read out loud as quickly as possible a number (1 to 6) presented on the screen for 100 ms. This additional condition was included in order to control for the time required by English speakers to pronounce each of the 6 possible responses used in the experiment.

2.2 *Results and discussion*

The mean RTs, percentages of errors, and the mean numerical responses obtained in the two conditions of tactile stimulus presentation are presented in figures 2a – 2c. Each of the three response measures was submitted to a repeated-measures ANOVA with the factors of numerosity (6 levels) and condition (fingertips versus body stimulus presentation).(3) The ANOVA on the RT data revealed a significant main effect of numerosity ($F_{5,50} = 47.01$, $p < 0.0001$), but not of condition ($F_{1,10} = 2.16$, ns). The interaction between condition and numerosity was also non-significant ($F_{5,50} = 1.93$, ns). The latencies of participants' responses increased as the number of stimuli presented in the display increased up to 3. When more than 3 stimuli were presented in the display, the participants' RTs remained constant.(4)

(3) A within-participants repeated-measures ANOVA with the factor of number (1 – 6) was conducted on the RT data from the participants' latencies to name digits presented on the computer screen. The results showed a significant main effect ($F_{5,50} = 8.72$, $p < 0.0001$). An a posteriori Scheffé test revealed significant differences between the following pairs of digits: 1 and 4 ($p = 0.02$; RTs were faster for 1 than for 4); 1 and 5 ($p = 0.003$; RTs were faster for 1 than for 5); 2 and 4 ($p = 0.01$; RTs were faster for 2 than for 4); 2 and 5 ($p = 0.001$; RTs were faster for 2 than for 5); 4 and 6 ($p = 0.03$; RTs were faster for 4 than for 6); 5 and 6 ($p = 0.004$; RTs were faster for 5 than for 6). The fact that significant differences between the latencies with which participants could verbalise the responses to the stimuli used in the experiment suggests that further caution should be adopted before drawing any firm conclusions based on vocal RTs in numerosity judgment tasks.

(4) Note, however, that this latter result might be an artifact, due to the procedure used to calculate the mean RTs for each numerosity. Indeed, the latencies of responses were calculated regardless of the accuracy of participant's responses; that is, they were calculated for both correct and incorrect responses. This procedure was adopted because the high number of errors made by the participants when more than 3 stimuli were presented limited the number of correct response data points available for the computation of the means.

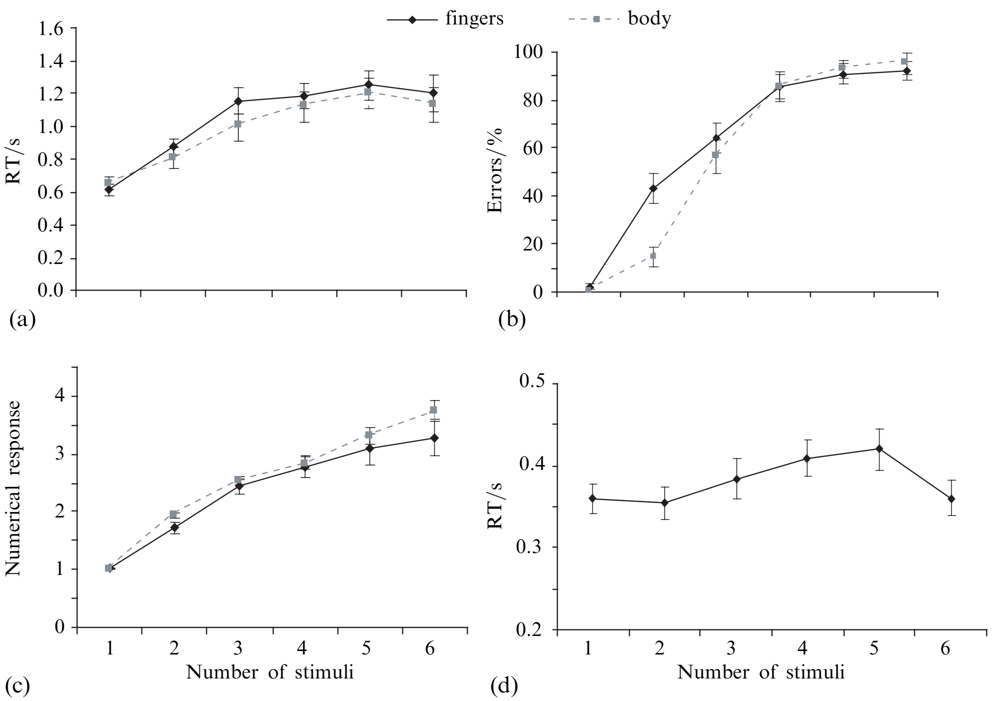

Figure 2. Performance of participants in the counting experiment reported in this paper. (a) – (c) Participants' responses in counting the tactile stimuli presented at any one time on the body surface (excluding the hands) versus on the fingertips, as a function of the number of stimuli presented in the display (1 – 6): (a) mean RTs; (b) mean percentages of errors; (c) mean numerical response. (d) Latency of participants' (English speakers) vocal responses in naming the digits 1 – 6 presented on a computer screen for 100 ms. Error bars represent ±1 SEM.

The ANOVA conducted on the error rates revealed a significant main effect of numerosity ($F_{5,50} = 206.18$, $p < 0.0001$), but not of condition ($F_{1,10} = 2.24$, ns). The interaction between condition and numerosity was also significant ($F_{5,50} = 5.13$, $p < 0.0001$). A Scheffé a posteriori test revealed a significant difference between the percentages of errors made by participants only when 2 stimuli were presented in the display ($p = 0.008$), but not for any of the remaining numerosities. For this numerosity, the percentage of errors was higher when the stimuli were presented on the fingertips than when they were presented across the body surface.

The ANOVA on the numerical responses given by the participants revealed a significant main effect of numerosity ($F_{5,50} = 206.18$, $p < 0.0001$), but not of condition ($F_{1,10} = 2.24$, ns). The interaction between condition and numerosity was borderline significant ($F_{5,50} = 2.31$, $p = 0.06$). The magnitude of the numerical responses given by the participants in both conditions of stimulus presentation increased as the number of stimuli presented in the display increased.

Linear, logarithmic, quadratic, power, sigmoid, exponential, and piecewise regression psychometrical analyses (with a pivot point at a numerosity of 3) were performed on both conditions of stimulus presentation for the RT and error data. The analysis of the goodness-of-fit based on a χ^2 merit function showed that the latencies predicted by the linear, exponential, and bilinear models were significantly different from those reported when the stimuli were presented on the fingertips. This analysis also revealed that the bilinear model was significantly different from the RT data obtained when the stimuli were presented on the body surface (while the data predicted by all of the other models were not significantly different from those obtained in the experiment).

The analysis of the goodness-of-fit on the error data showed that the data for the linear, power, sigmoid, exponential, and bilinear models were significantly different from the data obtained empirically in the condition where the stimuli were presented on the fingertips (while the data predicted by the logarithmic and quadratic models were not significantly different from those obtained in the experiment). The analysis also revealed that the data predicted by all of the models were significantly different from those obtained under conditions where the stimuli were presented on the fingertips. Note, also, that as far as the bilinear model is concerned, the slope of the function fitting the data below the pivot point (for a numerosity equal to 3; ie within the subitising range) was steeper than the slope of the curve fitting the data above the pivot point (ie in the counting range; see figures 2a and 2b, and Appendix, table A3), for both the errors and RT data, and for both conditions of stimulus presentation. This result is clearly incompatible with a subitising account of tactile numerosity judgments.

The data obtained from the experiment reported here confirm those reported previously by Gallace et al (2006), who found a lack of subitising for stimuli presented across the body surface, but not those reported by Riggs et al (2006), who claimed that subitising occurs for tactile perception when the stimuli are presented on the fingertips. One possible explanation that might account for the difference in the results reported here and those obtained by Riggs et al (2006) might be related to the duration of stimulus presentations used in the two studies (though see Gallace et al 2006 on this point). Specifically, while the fingers were stimulated for 100 ms in the present study, they were stimulated until a response was given in Riggs et al's study (resulting in a lower memory load; cf Gallace et al 2008). This difference might perhaps have led to an increase in the difficulty of the task of the present study, and thus to the overall larger number of errors reported here as compared to that reported in Riggs et al's study. One should also consider the possibility that when intervals are shorter than the time needed to shift attention or program and execute ocular movements between the stimuli presented (as in the present study) no discontinuity in numerosity judgments can be observed. This would clearly support the view that subitising (thought to be a pre-attentive process) does not affect tactile perception.

Note, however, that, although the accuracy of participants' responses in the present study was lower than that reported by Riggs et al (2006), this does not necessarily imply that our participants were not able to perform the task. Indeed, looking at the response data (see figure 2c), one can clearly see that the numerical responses given by the participants increased linearly with the number of stimuli presented in the display, just as reported previously by Gallace et al (2006; see also Gallace et al 2007a). That is, the participants were not simply responding randomly, but rather were systematically underestimating the number of stimuli presented in the display (just as in vision when large numbers of stimuli are presented in the display; eg Atkinson et al 1976a; see also Appendix, table A4).

A possible alternative interpretation for the lack of subitising in tactile perception might be related to the inhibitory interactions of inputs from simultaneous or near-simultaneous tactile inputs across the skin surface. Animal experiments have shown that vibrotactile stimuli presented simultaneously on different regions of the skin (on each hand) mutually suppress neural activity in the regions of the somatosensory cortex (SI) that represent the stimulated body parts (eg Tommerdahl et al 2005, 2006; see also Braun et al 2005 for a human study showing interference between stimuli presented simultaneously to the two hands in participants' localisation judgments). Note, however, that these interactions (thought to reflect the mediation of higher-level or integrative areas of the brain; see Tommerdahl et al 2006) have been so far reported only between the two hands, requiring further investigation in order to be extended to other regions of the skin (though see Alluisi et al 1965 for the suggestion that multiple tactile stimuli presented on different regions of the entire body surface might mutually interfere, as a consequence of some form of 'central masking'; see also Gallace et al 2007a).

In conclusion, we believe that it is only through the convergence of further psychophysical, neurophysiological, and neuroimaging studies that researchers will arrive at a more complete answer to the question whether subitising in touch should be considered as a psychological phenomenon with its own distinctive behavioural and physiological characteristics. Until such a time, it would appear that the main criterion for postulating a distinction between counting and subitising in tactile, and very likely also in visual, perception remains the particular preconceptions of the researchers involved. However, while waiting for new procedures to be adopted in order to definitively answer the question of whether subitising affects tactile perception, we believe that the principle of parsimony should be adopted by researchers in this field (see Sober 1981). That is, the statistical and experimental evidence (reported here) that a dual-system model (counting plus subitising) is not required in order to explain the data obtained by researchers in studies of tactile numerosity judgments, should suffice to rule out more complex proposals until new empirical evidence, that cannot be explained by a single-process hypothesis, is reported. Following on from this argument, and on the basis of the evidence provided by the new statistical analyses and the empirical data reported in the present paper, we would therefore suggest that a single-process model should be adopted (at least at the moment) in order to describe the limitations affecting the tactile processing of numerical information in humans (see also Gallace et al 2007a).

The present study demonstrates the importance of using exhaustive fitting and statistical procedures in order to test the validity of a specific theoretical model. We have also demonstrated that different conclusions regarding the presence versus absence of subitising in tactile perception can be drawn by using different fitting models. Specifically, we have shown that a bilinear model of the error data (supporting the presence of subitising in the tactile modality) with a change in the slope set to a numerosity of 3 is not actually predictive of the error data reported by Riggs et al (2006). We have also shown that a linear model of the error data does not provide the best fit for Gallace et al's (2006) data either. Note, however, that this result does not actually support the presence of subitising in touch, but it would eventually argue in favour of the presence of counting and numerical estimation procedures. A possible suggestion for future research in order to answer the question of whether two separate processes account for tactile numerosity judgments in humans might be to use matching-to-sample procedures rather than counting tasks (see Cantlon and Brannon 2006; Nieder and Miller 2004a, 2004b; Simons and Langheinrich 1982). Indeed, it is only by means of this procedure that one can plot Weber functions relative to the error data (note that this function embodies the concept that participants get 'progressively' less sensitive to stimulus change as the intensity increases). If Weber functions can be successfully used in order to fit participants' performance data this would strengthen the view that a single process is sufficient to explain numerosity judgments in humans (see Cantlon and Brannon 2006; Nieder and Miller 2004a, 2004b for the evidence that visual numerosity judgments in monkeys as well as in humans, when tested by matching-to-sample procedures, do not show any discontinuity between small and large numerosities and they can be fitted by Weber functions).

Acknowledgment. Our thanks go to Dr Joan López-Moliner for the useful suggestions regarding the analyses of the goodness-of-fit of the data reported in the manuscript.

References

Alluisi E A, Morgan B B Jr, Hawkes G R, 1965 "Masking of cutaneous sensations in multiple stimulus presentations" *Perceptual and Motor Skills* **20** 39 – 45

Atkinson J, Campbell F W, Francis M R, 1976a "The magic number 4 ± 0: A new look at visual numerosity judgments" *Perception* **5** 327 – 334

Atkinson J, Francis M R, Campbell F W, 1976b "The dependence of the visual numerosity limit on orientation, colour, and grouping in the stimulus" *Perception* **5** 335 – 342
Auvray M, Gallace A, Tan H Z, Spence C, 2007 "Crossmodal change blindness between vision and touch" *Acta Psychologica* **126** 79 – 97
Balakrishnan J D, Ashby F G, 1991 "Is subitizing a unique numerical ability?" *Perception & Psychophysics* **50** 555 – 564
Balakrishnan J D, Ashby F G, 1992 "Subitizing: Magical numbers or mere superstition?" *Psychological Research* **54** 80 – 90
Baron J, Pelli D G, 2006 "Crowding counting" *Journal of Vision* **6** 198a
Braun C, Hess H, Burkhardt M, Wühle A, Preissl H, 2005 "The right hand knows what the left hand is feeling" *Experimental Brain Research* **162** 366 – 373
Butterworth B, 1999 *The Mathematical Brain* (London: Macmillan)
Camos V, Barrouillet P, Fayol M, 2001 "Does the coordination of verbal and motor information explain the development of counting in children?" *Journal of Experimental Child Psychology* **78** 240 – 262
Cantlon J F, Brannon E M, 2006 "Shared system for ordering small and large numbers in monkeys and humans" *Psychological Science* **17** 401 – 406
Chi M T C, Klahr D, 1975 "Span and rate of apprehension in children and adults" *Journal of Child Psychology* **19** 434 – 439
Cowan N, 2001 "The magical number 4 in short-term memory: A reconsideration of mental storage capacity" *Behavioral and Brain Sciences* **24** 87 – 185
Cowan N, 2005 *Working Memory Capacity* (Hove: Psychology Press)
Gallace A, Spence C, 2008 "The cognitive and neural correlates of 'tactile consciousness': A multisensory perspective" *Consciousness and Cognition* **17** 370 – 407
Gallace A, Haggard P, Tan H Z, Spence C, 2008 "Short term memory for tactile stimuli" *Experimental Brain Research* **1190** 132 – 142
Gallace A, Tan H Z, Spence C, 2006 "Numerosity judgments for tactile stimuli distributed over the body surface" *Perception* **35** 247 – 266
Gallace A, Tan H Z, Spence C, 2007a "Multisensory numerosity judgments for visual and tactile stimuli" *Perception & Psychophysics* **69** 487 – 501
Gallace A, Tan H Z, Spence C, 2007b "The body surface as a communication system: The state of art after 50 years of research" *Presence: Teleoperators and Virtual Environments* **16** 655 – 676
Geldard F A, 1968 "Pattern perception by the skin", in *The Skin Senses* Ed. D R Kenshalo (Springfield, IL: Thomas) pp 304 – 321
Geldard F A, Sherrick C E, 1965 "Multiple cutaneous stimulation: The discrimination of vibratory patterns" *Journal of the Acoustical Society of America* **37** 797 – 801
Gert H, Joos V, 1979 "Effect on numerosity judgment of grouping of tones by auditory channels" *Perception & Psychophysics* **26** 374 – 380
Ginsburg N, Pringle L, 1988 "Haptic numerosity perception: Effect of item arrangement" *American Journal of Psychology* **101** 131 – 133
Hill J W, 1971 "Processing of tactual and visual point stimuli sequentially presented at high rates" *Journal of Experimental Psychology* **88** 340 – 348
James W, 1890/1950 *The Principles of Psychology* (New York: Dover Publications)
Jevons W S, 1871 "The power of numerical discrimination" *Nature* **3** 281 – 282
Kashino M, Hirahara T, 1996 "One, two, many—Judging the number of concurrent talkers" *Journal of the Acoustical Society of America* **99** 2596
Kaufman E, Lord M, Reese T, Volkmann J, 1949 "The discrimination of visual number" *American Journal of Psychology* **62** 498 – 525
Klahr D, Wallace J G, 1976 *Cognitive Development* (Hillsdale, NJ: Lawrence Erlbaum Associates)
Lakatos S, Shepard R N, 1997 "Time – distance relations in shifting attention between locations on one's body" *Perception & Psychophysics* **59** 557 – 566
Lechelt E C, 1974 "Some stimulus parameters on tactile numerousness perception", in *Conference on Vibrotactile Communication* Ed. F A Geldard (Austin, TX: Psychonomic Press) pp 1 – 5
Lechelt E C, 1975 "Temporal numerosity discrimination: Intermodal comparison revisited" *British Journal of Psychology* **66** 101 – 108
Loftin R B, 2003 "Multisensory perception: Beyond the visual in visualization" *Computing in Science & Engineering* **5** 56 – 58
Mandler G, Shebo J B, 1982 "Subitizing: An analysis of its component processes" *Journal of Experimental Psychology: General* **111** 1 – 22
Monty R A, 1962 "Auditory perception of numerosity as affected by number and by correct and incorrect knowledge of results" *Human Factors* **4** 193 – 199

Nakamura A, Yamada T, Goto A, Kato T, Ito K, Abe Y, Kachi T, Kakigi R, 1998 "Somatosensory homunculus as drawn by MEG" *NeuroImage* **7** 377 – 386

Narici L, Modena I, Opsomer R J, Pizzella V, Romani G L, Torrioli G, Traversa R, Rossini P M, 1991 "Neuromagnetic somatosensory homunculus: A non-invasive approach in humans" *Neuroscience Letters* **121** 51 – 54

Neter J, Kutner M, Nachtsheim C J, Wasserman W, 1990 *Applied Linear Statistical Models* (Homewood, IL: Irwin)

Nieder A, Miller E K, 2004a "A parieto-frontal network for visual numerical information in the monkey" *Proceedings of the National Academy of Sciences of the USA* **101** 7457 – 7462

Nieder A, Miller E K, 2004b "Analog numerical representations in Rhesus monkeys: Evidence for parallel processing" *Journal of Cognitive Neuroscience* **16** 889 – 901

Penfield W, 1950 *Cerebral Cortex of Man* (New York: Macmillan)

Peterson S, Simon T J, 2000 "Computational evidence for the subitising phenomenon as an emergent property of the human cognitive architecture" *Cognitive Science* **24** 93 – 122

Piazza M, Mechelli A, Butterworth B, Price C J, 2002 "Are subitizing and counting implemented as separate or functionally overlapping processes?" *NeuroImage* **15** 435 – 446

Pollack I, 1952 "The information of elementary auditory displays" *Journal of the Acoustical Society of America* **24** 745 – 749

Pylyshyn Z W, 1989 "The role of location indexes in spatial perception: A sketch of the FINST spatial-index model" *Cognition* **32** 65 – 97

Riggs K J, Ferrand L, Lancelin D, Fryziel L, Dumur G, Simpson A, 2006 "Subitizing in tactile perception" *Psychological Science* **17** 271 – 275

Sathian K, Simon T J, Peterson S, Patel G A, Hoffman J M, Grafton S T, 1999 "Neural evidence linking visual object enumeration and attention" *Journal of Cognitive Neuroscience* **11** 36 – 51

Simons D, Langheinrich D, 1982 "What is magic about the magical number four?" *Psychological Research* **44** 283 – 294

Sober E, 1981 "The principle of parsimony" *British Journal of Philosophical Sciences* **32** 145 – 156

Spence C, McGlone F P, 2001 "Reflexive spatial orienting of tactile attention" *Experimental Brain Research* **141** 324 – 330

Stevens S S, 1951 "Mathematics, measurement, and psychophysics", in *Handbook of Experimental Psychology* Ed. S S Stevens (New York: John Wiley) pp 23 – 35

Stevens S S, 1958 "Problems and methods of psychophysics" *Psychological Bulletin* **55** 177 – 196

Svenson O, Sjöberg K, 1978 "Subitizing and counting processes in young children" *Scandinavian Journal of Psychology* **19** 247 – 250

Taubman R E, 1950 "Studies in judged number: I. The judgment of auditory number" *Journal of General Psychology* **43** 167 – 194

Tommerdahl M, Simons S, Chiu J, Favorov O V, Whitsel B L, 2005 "Response to SI cortex to ipsilateral, contralateral, and bilateral flutter stimulation in the cat" *BMC Neuroscience* **6** 29

Tommerdahl M, Simons S, Chiu J, Favorov O V, Whitsel B L, 2006 "Ipsilateral input modifies the primary somatosensory cortex response to contralateral skin flutter" *Journal of Neuroscience* **26** 5970 – 5977

Trick L M, Pylyshyn Z W, 1993 "What enumeration studies can show us about spatial attention: Evidence for limited capacity preattentive processing" *Journal of Experimental Psychology: Human Perception and Performance* **19** 331 – 351

Trick L M, Pylyshyn Z W, 1994 "Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision" *Psychological Review* **101** 80 – 102

VanRullen R, Koch C, 2003a "Competition and selection during visual processing of natural scenes and objects" *Journal of Vision* **3** 75 – 85

VanRullen R, Koch C, 2003b "Is perception discrete or continuous?" *Trends in Cognitive Sciences* **7** 207 – 213

Warren H C, 1897 "The reaction time of counting" *Psychological Review* **101** 80 – 102

Weiss W, 1965 "Influence of an irrelevant stimulus attribute on numerosity judgments" *Perceptual and Motor Skills* **21** 404

White C T, Cheatham P G, Armington J C, 1953 "Temporal numerosity: II. Evidence for central factors influencing perceived number" *Journal of Experimental Psychology* **46** 283 – 287

Wolters G, Kempen H van, Wijlhuizen G-J, 1987 "Quantification of small numbers of dots: Subitizing or pattern recognition?" *American Journal of Psychology* **100** 225 – 237

Appendix

Table A1. Parameters and goodness-of-fit of the functions fitted to the RT data and their statistical analysis in Riggs et al's (2006) study and in Gallace et al's (2006) study. Note that in (b) and (d) χ values higher than the critical value of χ (ie corresponding to $p = 0.05$) indicate that the data expected by a given model were significantly different from the data actually reported experimentally. (Asterisked values in these tables indicate values of χ lower than the critical χ value, thus showing that the functions provided a valid fit to the data.) Bilinear 3 and 4 are the functions with pivot points at numerosity values of 3 and 4, respectively.

(a) Parameters of the functions fitted to Riggs et al's (2006) data

	r^2	F	p	Parameter estimates				Fitting function
				constant (b_0)	b_1	b_2	pivot	
Linear	0.96	120.47	0.00	110.6667	464.2857			$Y = b_0 + b_1 X$
Logarithmic	0.82	18.76	0.01	409.2081	1209.674			$Y = b_0 + b_1 \ln X$
Quadratic	0.99	961.24	0.00	638	68.78571	56.5		$Y = b_0 + b_1 X + b_2 X^2$
Power	0.93	53.31	0.00	667.3261	0.768646			$Y = b_0 X^{b_1}$
Sigmoid	0.75	12.65	0.02	7.945989	−1.46904			$Y = e^{b_0 + \frac{b_1}{X}}$
Exponential	0.99	1438.34	0.00	577.9679	0.281889			$Y = b_0 e^{b_1 X}$
Bilinear 3	0.99	2214.12	0.00	1273.08	253.05	589.1	3	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$
Bilinear 4	0.99	228.06	0.00	1759.92	351.68	654.84	4	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$

(b) χ^2 goodness of fit

	χ	χ for $p = 0.05$
Linear	55.75	11.07
Logarithmic	221.6	11.07
Quadratic	0.77*	11.07
Power	40.04	11.07
Sigmoid	3109524	11.07
Exponential	1048	11.07
Bilinear 3	0.91*	11.07
Bilinear 4	9.59*	11.07

Table A1 (continued)

(c) Parameters of the functions fitted to Gallace et al's (2006) data

	r^2	F	p	Parameter estimates				Fitting function
				constant (b_0)	b_1	b_2	pivot	
Linear	0.988774	352.31	0.00	906	144			$Y = b_0 + b_1 X$
Logarithmic	0.9582	91.69	0.00	971.1446	400.2176			$Y = b_0 + b_1 \ln X$
Quadratic	0.995343	320.56	0.00	831	200.25	−8.03571		$Y = b_0 + b_1 X + b_2 X^2$
Power	0.980267	198.71	0.00	1000.871	0.297822			$Y = b_0 X^{b_1}$
Sigmoid	0.863892	25.38	0.00	7.476615	−0.59122			$Y = e^{b_0 + \frac{b_1}{X}}$
Exponential	0.97477	154.54	0.00	960.092	0.105192			$Y = b_0 e^{b_1 X}$
Bilinear 3	0.9917	178.68	0.00	1359.47	163.68	132.36	3	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$
Bilinear 4	0.9966	445.49	0.00	1517.36	163.157	111.57	4	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$

(d) χ^2 goodness of fit

	χ	χ for $p = 0.05$
Linear	0.12*	11.07
Logarithmic	1.11*	11.07
Quadratic	0.05*	11.07
Power	0.41*	11.07
Sigmoid	635895	11.07
Exponential	15.37	11.07
Bilinear 3	0.07*	11.07
Bilinear 4	0.04*	11.07

Table A2. Parameters and goodness-of-fit of the functions fitted to the error data and their statistical analysis in Riggs et al's (2006) study and in Gallace et al's (2006) study. Note that in tables (b) and (d) χ values higher than the critical value of χ (ie corresponding to $p = 0.05$) indicate that the data expected by a given model were significantly different from the data actually reported experimentally. (Asterisked values in these tables indicate values of χ lower than the critical chi value, thus showing that the functions provided a valid fit to the data.) Bilinear 3 and 4 are the functions with pivot points at numerosity values of 3 and 4, respectively.

(a) Parameters of the functions fitted to Riggs et al's (2006) data

	r^2	F	p	Parameter estimates				Fitting function
				constant (b_0)	b_1	b_2	pivot	
Linear	0.93	50.92	0.00	−16.67	10.57			$Y = b_0 + b_1 X$
Logarithmic	0.76	12.51	0.02	−9.25	26.98			$Y = b_0 + b_1 \ln X$
Quadratic	0.98	74.54	0.00	−0.50	1.55	1.73		$Y = b_0 + b_1 X + b_2 X^2$
Power	0.95	72.57	0.00	0.68	2.38			$Y = b_0 X^{b_1}$
Sigmoid	0.81	17.37	0.01	4.13	−4.66			$Y = e^{b_0 + \frac{b_1}{X}}$
Exponential	0.95	79.78	0.00	0.48	0.84			$Y = b_0 e^{b_1 X}$
Bilinear 3	0.98	114.70	0.00	7.64	3.78	14.57	3	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$
Bilinear 4	0.95	33.51	0.00	20.38	7.73	15.36	4	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$

(b) χ^2 goodness of fit

	χ	χ for $p = 0.05$
Linear	1056	11.07
Logarithmic	2351	11.07
Quadratic	47.38	11.07
Power	15.96	11.07
Sigmoid	2023	11.07
Exponential	19531	11.07
Bilinear 3	28.38	11.07
Bilinear 4	332	11.07

Table A2 (continued)

(c) Parameters of the functions fitted to Gallace et al's (2006) data

	r^2	F	p	Parameter estimates				Fitting function
				constant (b_0)	b_1	b_2	pivot	
Linear	0.93	50.92	0.00	−16.67	10.57			$Y = b_0 + b_1 X$
Logarithmic	0.76	12.51	0.02	−9.25	26.98			$Y = b_0 + b_1 \ln X$
Quadratic	0.98	74.54	0.00	−0.50	−1.55	1.73		$Y = b_0 + b_1 X + b_2 X^2$
Power	0.95	72.57	0.00	0.68	2.38			$Y = b_0 X^{b_1}$
Sigmoid	0.81	17.37	0.01	4.13	−4.66			$Y = e^{b_0 + \frac{b_1}{X}}$
Exponential	0.95	79.78	0.00	0.48	0.84			$Y = b_0 e^{b_1 X}$
Bilinear 3	0.98	114.70	0.00	7.64	3.78	14.57	3	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$
Bilinear 4	0.95	33.51	0.00	20.38	7.73	15.36	4	$Y = \begin{cases} b_0 + b_1 (X - \text{pivot}) & \textit{if } X < \text{pivot} \\ b_0 + b_2 (X - \text{pivot}) & \text{otherwise} \end{cases}$

(d) χ^2 goodness of fit

	χ	χ for $p = 0.05$
Linear	46.62	11.07
Logarithmic	17.87	11.07
Quadratic	8.67*	11.07
Power	179.28	11.07
Sigmoid	133811	11.07
Exponential	48262	11.07
Bilinear 3	9.29*	11.07
Bilinear 4	2.82*	11.07

Table A3. Parameters of the functions (ie linear and bilinear with pivot point set to 3) and goodness-of-fit (χ^2) of the functions fitted to the error data (a) and the RT data (b) for stimuli presented on the body surface (excluding the hands) versus on the fingertips, obtained in the present study. Note that χ values higher than the critical value of χ (ie corresponding to $p = 0.05$) indicate that the data expected by a given model are significantly different from the data actually reported experimentally. (Asterisked values in these tables indicate values of χ lower than the critical χ value, thus showing that the functions provided a valid fit to the data.)

	Fingers					Body					χ for $p = 0.05$
	b_0	b_1	b_2	r^2	χ	b_0	b_1	b_2	r^2	χ	
(a) *Error data*											
Linear	1.29	17.61		0.86	103.77	−16.16	21.04		0.91	78.34	11.07
Logarithmic	4.88	52.93		0.98	7.90*	−8.48	60.14		0.93	230.83	11.07
Quadratic	−42.64	50.48	−4.69	0.99	1.16*	−48.78	45.50	−3.49	0.96	148.52	11.07
Power	3.96	2.08		0.81	416.76	1.17	2.84		0.90	536.29	11.07
Sigmoid	5.62	−4.78		0.96	91.67	5.87	−6.31		0.99	55.82	11.07
Exponential	4.27	0.63		0.59	699.65	1.17	0.89		0.70	1255.01	11.07
Bilinear (3)	71.58	33.62	8.14	0.98	1535.59	59.53	32.57	14.23	0.95	8972.26	11.07
(b) *RT data*											
Linear	0.63	0.12		0.76	21.26	0.61	0.11		0.86	5.33*	11.07
Logarithmic	0.64	0.36		0.92	3.83*	0.63	0.31		0.94	1.74*	11.07
Quadratic	0.23	0.41	−0.04	0.98	1.30*	0.35	0.29	−0.02	0.98	7.50*	11.07
Power	0.65	0.40		0.91	6.27*	0.65	0.35		0.95	1.66*	11.07
Sigmoid	0.37	−0.87		0.97	2.95*	0.25	−0.75		0.92	3.64*	11.07
Exponential	0.64	0.12		0.73	23.96	0.63	0.11		0.84	7.41*	11.07
Bilinear (3)	1.16	0.27	0.02	0.99	2592.43	1.02	0.19	0.05	0.95	1713.19	11.07

Table A4. Confusion matrices for (a) the finger-presentation and (b) the body-presentation conditions in the experiment reported, showing the number of times participants made each response (1 to 6) when a given number of tactors was activated (note that the theoretical maximum for each cell is 165). The italicised values represent the number of correct responses. Values below the diagonal connecting the upper-left corner and the lower-right corner of the table represent participants' underestimations of the number of tactors presented in the display, while values above such diagonal represent participants' overestimations.

Number of tactors activated	Response					
	1	2	3	4	5	6
(a) *Finger presentation*						
1	*162*	3	0	0	0	0
2	59	*93*	11	0	1	0
3	14	79	*59*	12	1	0
4	8	62	64	*24*	4	3
5	7	46	63	29	*14*	4
6	7	40	51	38	16	*10*
(b) *Body presentation*						
1	*164*	1	0	0	0	0
2	18	*141*	6	0	0	0
3	2	82	*72*	9	0	0
4	2	49	89	*24*	1	0
5	1	19	83	50	*11*	0
6	0	7	56	83	11	*8*

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 37 2008

www.perceptionweb.com