

Why the whole is more than the sum of its parts: Salience-driven overestimation in aggregated tactile sensations

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Complete List of Authors:	Cataldo, Antonio; University College London Institute of Cognitive Neuroscience, Ferrè, Elisa; Royal Holloway University of London, Psychology di Pellegrino, Giuseppe; University of Bologna, Psychology Haggard, Patrick; University College London Institute of Cognitive Neuroscience,
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Corresponding Author
Patrick Haggard, Institute of Cognitive Neuroscience, 17 Queen Square,
London, WC1N 3AZ, United Kingdom.
Tel.: +44 (0)20 7679 1177
Email address: p.haggard@ucl.ac.uk

Article title
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in aggregated tactile sensations

Short title
Saliency-driven overestimation in touch

Authors
Antonio Cataldo^{a b c}, Elisa Raffaella Ferrè^d, Giuseppe di Pellegrino^b, & Patrick
Haggard^{a c}

Abstract
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to minimal sensory units, such as thresholds or just noticeable differences in a
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inputs to a sensory system are aggregated into an overall percept. Participants
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depends on the ability to consciously perceive discrepancy among components
(Experiment 1), whether the discrepancy among these components influences
sensitivity or/and perceptual bias in judging totals (Experiment 2), and whether
the saliency of each individual component stimulus affects perception of total
intensity (Experiment 3). Perceptual aggregation of two simultaneous component
events occurred both when participants could perceptually discriminate the two
intensities, and also when they could not. Further, the actual discrepancy
between the stimuli modulated both participants' sensitivity and perceptual bias:
increasing discrepancies produced a systematic and progressive overestimation
of total intensity. The degree of this bias depended primarily on the saliency of
the stronger stimulus in the pair. Overall, our results suggest that important
nonlinear mechanisms contribute to sensory aggregation. The mind aggregates
component inputs into a coherent and synthetic perceptual experience in a
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Why the whole is more than the sum of its parts: Saliency-driven overestimation in aggregated sensations

Antonio Cataldo^{a b c}, Elisa Raffaella Ferrè^d, Giuseppe di Pellegrino^b, & Patrick Haggard^{*a c}

a. Institute of Cognitive Neuroscience, University College London, Alexandra House 17 Queen Square, London WC1N 3AZ, UK

b. Centre for Studies and Research in Cognitive Neuroscience, Alma Mater Studiorum - University of Bologna, Viale Europa 980, 47521 Cesena, Italy

c. Institute of Philosophy, School of Advanced Study, University of London, Senate House, Malet Street, London, WC1E 7HU

d. Department of Psychology, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK.

* Corresponding author. Address: Institute of Cognitive Neuroscience, 17 Queen Square, London, WC1N 3AZ, United Kingdom. Tel.: +44 (0)20 7679 1177. Email address: p.haggard@ucl.ac.uk

Abstract

Experimental psychology often studies perception analytically, reducing its focus to minimal sensory units, such as thresholds or just noticeable differences in a single stimulus. Here, in contrast, we examine a synthetic aspect: how multiple inputs to a sensory system are aggregated into an overall percept. Participants in three experiments judged the total stimulus intensity for simultaneous electrical shocks to two digits. We tested whether the integration of component somatosensory stimuli into a total percept occurs automatically, or rather depends on the ability to consciously perceive discrepancy among components (Experiment 1), whether the discrepancy among these components influences sensitivity or/and **perceptual bias** in judging totals (Experiment 2), and whether the salience of each individual component stimulus affects perception of total intensity (Experiment 3). Perceptual aggregation of two simultaneous component events occurred both when participants could perceptually discriminate the two intensities, and also when they could not. Further, the actual discrepancy between the stimuli modulated both participants' sensitivity and **perceptual bias**: increasing discrepancies produced a systematic and progressive overestimation of total intensity. The degree of this bias depended primarily on the salience of the stronger stimulus in the pair. Overall, our results suggest that important nonlinear mechanisms contribute to sensory aggregation. The mind aggregates component inputs into a coherent and synthetic perceptual experience in a salience-weighted fashion that is not based on simple summation of inputs.

Keywords

Somatosensory integration, nonlinear summation, tactile perception, digital nerve stimulation.

Introduction

Most studies of tactile perception focussed on how *single tactile events* are detected (LaMotte & Whitehouse, 1986; Johansson, Vallbo, & Westling, 1980), localized (Sherrick, Cholewiak, & Collins, 1990; Harris, Thein, and Clifford, 2004; Porro, et al., 2007), and identified (Johnson & Phillips, 1981; Stevens & Patterson, 1995). Such isolated single stimuli are rare in daily life. Rather, we continually experience multiple, simultaneous, non-homogeneous stimuli spread across several skin locations, yet the brain may still generate a single, coherent percept. For instance, when we hold an object between our fingertips we do not perceive five distinct sensations. Rather, we have an immediate and synthetic perception of the whole grasped object.

Simultaneous inputs coming from each finger must be combined along the somatosensory pathways to generate such coherent, multi-touch percepts (Gallace & Spence, 2014; Martin, 1992; MacKay, 1967). This process is limited by both intersensory interactions and by bandwidth (Gallace & Spence, 2014; Cohen, Dennett, & Kanwisher, 2016). For example, two or more somatosensory stimuli may interact, rather than simply sum linearly. Studies on *vibro-tactile masking* (Craig, 1976; von Békésy, 1967) and the *double simultaneous stimulation paradigm* (Sherrick, 1964; Tamè, Farnè, & Pavani, 2011), show that tactile detection drastically deteriorates when the stimulus is presented in spatial and temporal proximity with a distractor. Second, studies on *tactile subitizing* (Gallace, Tan, & Spence, 2006a; Plaisier, Bergmann Tiest, & Kappers, 2009; Riggs et al., 2006; for a review see Gallace, Tan, & Spence, 2008) show that both errors and response times in an enumeration task dramatically increase when two or more vibro-tactile stimuli are delivered simultaneously.

Intensity is a fundamental dimension of all perceptual channels (Bensmaia, 2008), and has been widely explored (Gescheider et al., 2004; Gibson & Tomko, 1972; Marks,

1979; Verrillo & Gescheider, 1975; Bolanowski et al 1988; Craig, 1972, 1974). Yet, perception of the overall intensity of combined multi-touch stimuli has rarely been studied (Tamè, Moles & Holmes, 2014; Walsh et al., 2016). Walsh and colleagues (2016) asked participants to judge the overall intensity of electro-tactile stimulation simultaneously delivered to two fingers of the same hand. The intensity of each stimulus in the pair was manipulated in order to obtain different levels of discrepancy in the percept, while keeping the overall physical intensity constant. If somatosensory intensity perception is based on linear summation of component stimuli, uneven distribution of physical intensity across the fingers should not affect perception of total intensity. In fact, Walsh et al. (2016) found that participants' accuracy in judging the total intensity drastically decreased as the discrepancy between the two stimuli increased. In particular, the total intensity of discrepant stimuli was systematically overestimated, suggesting that the mechanism for aggregating the component stimuli was strongly biased by the peak stimulus. That is, the most salient input (i.e. the strongest stimulus in a discrepant pair) made a disproportionately strong contribution to the perception of the total. Importantly, Walsh et al., (2016) ruled out the possibility that the weak stimulus in the pair was simply extinguished, suggesting that the overestimation bias is an effect of stimuli's aggregation.

The mechanisms underlying this interesting perceptual nonlinearity remain unclear. Such effects could reflect perceptual interactions between component stimuli, limited bandwidth for transmitting multiple stimuli to awareness, or both of these factors. Therefore, we used discrepant and non-discrepant electro-tactile patterns to investigate how the intensity of multiple simultaneous somatosensory events is integrated into a holistic percept. First, Experiment 1 tested whether individuals' ability in judging the overall intensity of two simultaneous stimuli was related to the ability to consciously perceive discrepancy between the component stimuli. Our results indicate that

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3 participants made accurate overall intensity judgements despite a surprisingly poor ability
4 to detect intensity discrepancy between the component stimuli, suggesting an automatic
5 process of aggregation.
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10 Second, we investigated whether the intensity overestimation described by Walsh
11 at al. (2016) is a genuine perceptual process or alternatively is driven by changes in
12 response bias (Experiment 2). Our results indicate that as the intensity discrepancy
13 between two stimuli increased, perceptual sensitivity to total intensity decreased, and
14 participants' **perceptual bias** become more liberal, leading to overestimates of total
15 intensity.
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23 Experiment 3 compared the perceived intensity of double stimuli to that of single
24 stimuli. We found that the perceived overall intensity of two discrepant stimuli was
25 almost entirely explained by the intensity of the strongest component stimulus. The peak
26 intensity of a multi-touch somatosensory stimulation has a disproportionate influence on
27 judgements of total intensity.
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38 Methods

39 Experiment 1. Aggregation and discrimination of the parts for the 40 perception of the whole

41 Experiment 1 aimed to compare participants' accuracy in aggregating versus
42 discriminating the intensity of two tactile stimuli. In addition to this, we used less-
43 frequent "rating trials" to investigate whether information about the intensity of the
44 individual components was affected by the context of global judgements regarding
45 aggregates or discriminanda.
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Participants

Twenty healthy right-handed volunteers (10 female, mean age \pm SD: 25.5 \pm 4.1 years) participated in Experiment 1. Two of them were excluded because the tactile stimulation range (i.e. the range between the detection threshold and the pain threshold to electrical stimulation of the digital nerves) was too small to generate the whole set of experimental stimuli required by our design (stimulation range < 2 mA; see below). Data from two further participants were lost due to a technical error. The final sample size of Experiment 1 (n = 16) was decided *a priori*, on the basis of previous similar studies (Walsh et al., 2016). The experimental protocol was approved by the research ethics committee of University College London, and adhered to the ethical standards of the Declaration of Helsinki.

Experimental setup

Transcutaneous electrical tactile stimuli were delivered through a Digitimer DS5 constant current stimulator (Digitimer, Ltd., United Kingdom), controlled by a computer. A pair of stainless digital ring electrodes (Technomed Europe, Netherlands) was applied to the proximal and intermediate phalanges of index and middle fingers of the right hand. Electrical impedance between each electrode and the skin was kept below 5k Ω throughout the experiment by means of self-adhesive conductive gel patches. Participants were asked to rest their right-hand palm downwards on a table. Particular care was taken to make sure that the ring electrodes did not touch each other, and that the only points of contact between the hand and the surface of the table were the thenar and hypothenar eminences, the distal finger pads of digits 2–5 and the lateral side of the thumb pad. Vision of the hand was blocked by a screen. Instructions before and during the task were presented using the Psychophysics Toolbox v3 (<http://psychtoolbox.org>) for MATLAB.

Before the experiment started, detection and pain thresholds were established for each participant. The procedure was based on the methods described by Walsh and colleagues (2016). In a staircase procedure, the same stimulation intensity was delivered simultaneously to both fingers starting from 0.5 mA and increasing in steps of 0.5 mA until the participant perceived the stimulus. After the first detection, the current was reduced in steps of 0.5 mA until the stimulus was no longer perceived, and then increased once again. The current intensity able to evocate the second detection was taken as participant's detection threshold. Pain threshold was established with the same procedure, but in this case, participants were asked to report whether the stimulation was painful or not. In order to set stimulus values within the participants' tactile range only, we selected current intensities that were clearly above detection threshold (floor: 1.5 x detection threshold), yet below pain threshold (ceiling: 90% of pain threshold). Then, small and large total intensities were set at 37.5% and 62.5% of the stimulation range for each participant.

Next, in a pre-testing phase, we verified that participants' accuracy in judging the total intensity of non-discrepant pairs would avoid ceiling and floor effects when testing our experimental hypotheses. A series of non-discrepant pairs with small or large intensity were simultaneously delivered on the index and middle fingers, and participants were asked to judge the overall intensity of each pair by pressing one of two keys corresponding to "small"/"large" total. At the beginning of the block, participants were presented with a small and a large total example. Performance was checked after 20 trials. If accuracy was below 60% or above 80%, the difference between the two totals was increased or decreased respectively, and the block was repeated until performance lay between these limits. The group mean final accuracy \pm SD was: 75.6% \pm 6.8%.

Finally, from each non-discrepant pair, we derived a discrepant pair characterized by the 70% of the maximum possible discrepancy within the stimulation range (see Figure 1).

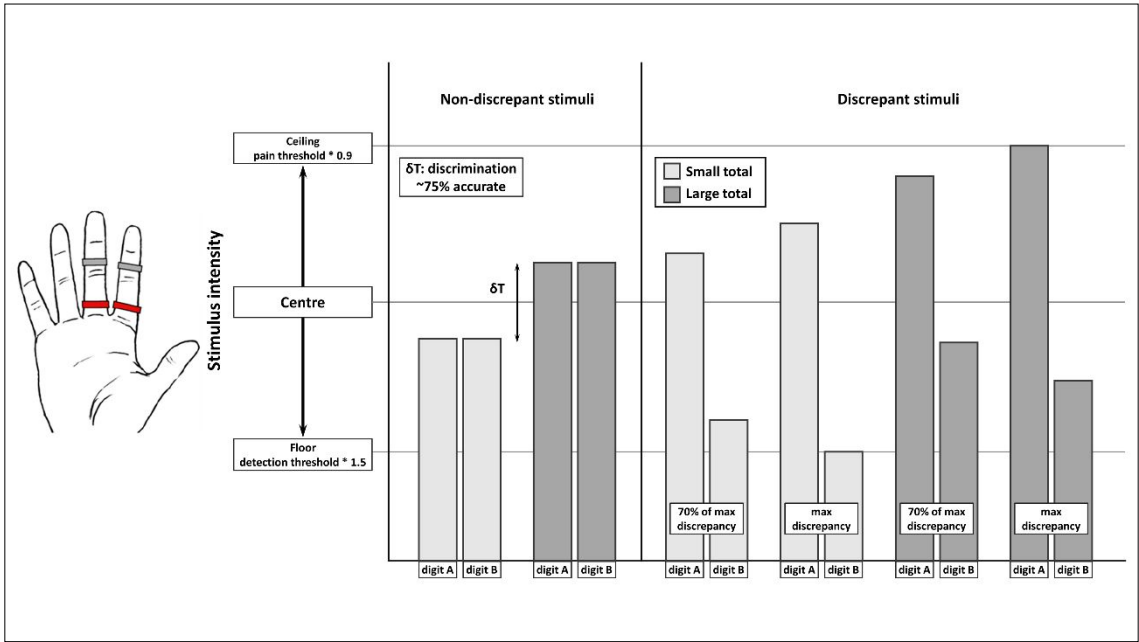


Figure 1. Stimulation levels for Experiment 1 (non-discrepant stimuli and 70% discrepant stimuli) and Experiment 2 (all the stimuli). In both experiments, electrodes were placed on participants' right index and middle fingers. The intensity of the electro-tactile stimulation in each condition was established on the basis of individual detection and pain thresholds. For non-discrepant stimulus pairs, intensities were chosen so that participants discriminated small from large stimuli at approximately 75% correct. In Experiment 1 stimulus pairs were based on 70% of this maximal discrepancy. In Experiment 2, aside the 70% discrepant stimuli, maximally discrepant stimuli spanned the range from detection to pain thresholds, and were total-matched to non-discrepant stimuli.

Procedure

In two separate blocks, participants performed either an aggregation (“judge the total intensity of the pair”) or a discrimination (“judge the discrepancy of the pair”) task on exactly the same combination of stimuli. We decided to test participants’ aggregation/discrimination ability in two separate blocks (1) to prevent potential errors

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3 due to the continue task-switching required by a full-randomisation paradigm, and (2) to
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5 prevent cognitive and perceptual overload.
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8 Participants were delivered with both a discrepant and a non-discrepant pair,
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10 separated by 1s delay. One of the pairs had the large total intensity and the other the small
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12 total intensity. Participants performed a two-interval forced choice task, judging which
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14 pair had the larger overall intensity (aggregation task) or the larger discrepancy between
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16 the two intensity (discrimination task). The stimuli in both tasks were identical. In a
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18 small subset of trials (rating trials: 17%), randomly distributed across each block,
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20 participants were instead presented with a single discrepant pair, and were asked to rate
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22 the intensity of either the strong stimulus or the weak stimulus in the pair between 1 (very
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24 weak) to 10 (very strong). These rating trials allowed us to assess how well the
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26 component stimuli within a pair were perceived. We specifically aimed to compare
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28 perception of individual component stimuli between blocks where the primary task was
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30 either aggregation or discrimination. To anchor their magnitude estimation on rating
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32 trials, participants were presented with the limits (floor and ceiling) of their stimulation
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34 range, at the beginning of each block and after every 20 trials.
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40 Participants performed two blocks (Aggregation task, Discrimination task). Each
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42 block consisted of 192 trials (160 main trials plus 32 rating trials), for a total of 384 trials.
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44 The order of the task (aggregation/discrimination) was counterbalanced between
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46 participants. The presentation order of small/large and discrepant/non-discrepant pairs,
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48 the localization of the strong stimulus in discrepant pairs (index/middle), and the target
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50 of the rating trials (strong/weak stimulus) were counterbalanced within participants.
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57 Experiment 2. Sensitivity and perceptual bias in judgements of
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Experiment 2 aimed to investigate whether the tendency to overestimate the total intensity of discrepant stimuli (Walsh et al., 2016) reflects a change in participants' sensitivity and/or perceptual bias.

Participants

Twenty participants (10 female, mean age \pm SD: 25.7 \pm 2.4 years) took part in Experiment 2. The experimental protocol was approved by the research ethics committee of the Department of Psychology of the University of Bologna. The study adhered to the ethical standards of the Declaration of Helsinki. Participants provided their written informed consent before the beginning of the experiment.

Experimental setup

Transcutaneous electrical nerve stimulation was delivered by means of a Digitimer DS7 constant current stimulator (Digitimer, Ltd., United Kingdom). Two pairs of self-adhesive surface electrodes (SU15N1 electrodes, SEI EMG, Padova) connected to the stimulator were applied to the hairy skin of proximal and intermediate phalanges of participants' index and middle fingers. Instructions before and throughout the experiment were presented using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA), while stimulation was delivered using custom software. Participants rested their right hand palm down on a table. Vision of the stimulated hand was blocked with a screen.

The procedure for establishing tactile detection and pain thresholds was the same as Experiment 1. The floor and ceiling levels were set at 2 x detection threshold and 90% of the pain threshold, respectively. Again, we selected the 37.5% and 62.5% of the stimulation range as small and the large total intensities. Next, we subdivided each total

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3 in three different levels of discrepancy: 0% (no discrepancy between the two stimuli),
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5 70% (low discrepancy) and 100% (maximum discrepancy) (see Figure 1).
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8 Participants performed a brief familiarization task where 30 non-discrepant small
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10 and large pairs were sequentially presented in random order. Each stimulus was
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12 associated to an audible beep. Participants were asked to judge the overall intensity of
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14 each pair by pressing one of two keys corresponding to “small”/“large” total. At the end
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16 of the task, accuracy was checked (group mean accuracy \pm SD: 81.6% \pm 7.6%).
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21 Procedure

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23 The procedure of the main experiment was identical to the familiarization task
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25 described above, with the only exception that each small/large total was delivered at one
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27 out of the three different levels of discrepancy (0%, 70%, and 100%). The presentation
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29 order of the stimuli and the localization of the strongest stimulus in the discrepant trials
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31 (index/middle finger) were randomized within participants. Each stimulus was repeated
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33 40 times, giving a total of 240 trials. Participants were given a short break every 60 trials.
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41 Experiment 3. Perceived intensity of discrepant and non- 42 discrepant double tactile stimulations

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44 Experiment 3 aimed to compare directly the perceived intensity of double simultaneous
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46 stimulations, either discrepant or non-discrepant, with the perceived intensity of single
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48 stimuli.
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54 Participants

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56 Fourteen participants (10 female, mean age \pm SD: 23.9 \pm 4.1 years) participated in
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58 Experiment 3. Four of these were excluded because their electro-tactile stimulation range
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was too small (i.e. < 3 mA), leaving a final sample size of $n = 10$. The experimental protocol was approved by the research ethics committee of University College London. The study adhered to the ethical standards of the Declaration of Helsinki. Participants provided their written informed consent before the beginning of the experiment.

Experimental setup

We used the same experimental setup as in Experiment 1. However, three fingers (index, middle and ring fingers) were stimulated during the experiment. Detection and pain threshold were assessed separately for each digit in order to level out any eventual difference in the perception of electro-tactile stimulation due to physical difference between the fingers.

In order to extend the range of tactile stimuli deliverable, we established the floor at $1.2 \times$ detection threshold, and the ceiling at $90\% \times$ pain threshold of the index finger. Then, we set the intensity of the non-discrepant stimulus at 37.5% of participants' stimulation range. We calculated the intensities at 70% of the maximum possible discrepancy for the same total intensity. Then, for each of the three stimulation levels established for the index finger we used a staircase procedure to find the corresponding perceived isointensities for the middle and ring fingers, separately. In each staircase, one of the three reference intensities was delivered to the index finger first. After 500msec , a comparison stimulus was presented on the target digit (middle or ring finger). Participants were asked to press a key to adjust the physical intensity of the second stimulus until it matched the intensity of the reference stimulus. At the beginning of the staircase procedure, the step size was set at 10% of participant's maximal stimulation level for their ring finger (i.e. their pain threshold for ring finger). After the first reversal, the step size was reduced from 10% to 5% of participant's pain threshold for ring finger.

The staircase procedure ended after seven reversals, and the average of the last three reversals was taken as the stimulation level for the target finger.

Procedure

Experiment 3 aimed to compare the perceived intensity evoked by single (small/large) and double (non-discrepant/discrepant) tactile stimulations.

The experiment was divided in four blocks. In each block, participants were presented with one ascending and one descending staircase for each of four experimental conditions: (1) single small stimulation, (2) single large stimulation, (3) double non-discrepant stimulation, and (4) double discrepant stimulation (see Figure 2). The single small stimulus corresponded to the intensity of one stimulus of the non-discrepant pair, while the single large stimulus corresponded to the strongest stimulus of a discrepant pair. The position of the strong stimulus (index/middle finger) in condition 4 (double discrepant stimulation) was counterbalanced across two separate staircases, and the results from the two staircases were pooled together. The staircase procedure was similar to that described above for the pre-testing phase. In each trial, a reference stimulus was presented on the index finger alone (single stimulation) or on index and middle fingers simultaneously (double stimulation). The comparison stimulus, instead, was always delivered on the ring finger. The four blocks were presented in a counterbalanced order across participants. In each block, the two staircases (starting from the floor or the ceiling level of the ring finger) were randomly interleaved. Each staircase ended after seven reversals, and the average of the last three reversals was taken as a measure of the perceived intensity in each condition (Levitt, 1970).

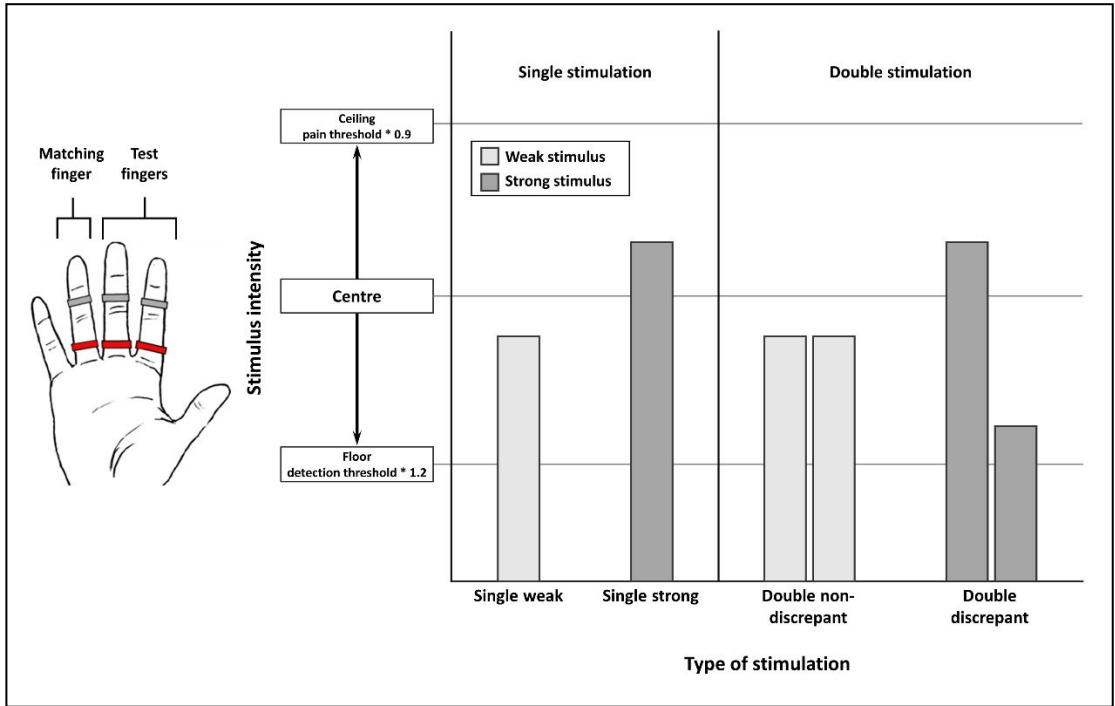


Figure 2. Stimulation of index and middle fingers in Experiment 3, was discrepant or non-discrepant as in Experiment 1. Additional trials delivered weak or strong stimuli either to index or middle fingers alone, matching the intensity of component stimuli in stimulus pairs. Participants adjusted shocks to ring finger to have the same perceived intensity of the stimuli delivered to index and middle fingers.

Results

Experiment 1

To assess whether discrimination of the parts is required in for total intensity perception, we performed a 2 (judgement: aggregation/discrimination) x 2 (total intensity: small/large) repeated measures ANOVA on the accuracy level showed in each condition (see Figure 3). We found a significant main effect of judgement ($F(1, 15) = 14.357; p = 0.002; \eta^2 = 0.489$). Participants' accuracy in the aggregation task was significantly higher (mean \pm SD: $81.5\% \pm 13.3\%$) than that in the discrimination task (mean \pm SD: $61.88\% \pm 22.4\%$). The main effect of total intensity ($F(1, 15) = 0.122; p = 0.732$) and the interaction between factors ($F(1, 15) = 1.115; p = 0.308$) were both non-significant. If

aggregation were to depend critically on discrimination, then aggregation performance could not exceed discrimination performance. In fact, the converse was found. Therefore, accurate judgements of total intensity (i.e. aggregation) were possible even for some stimuli that were not readily discriminable.

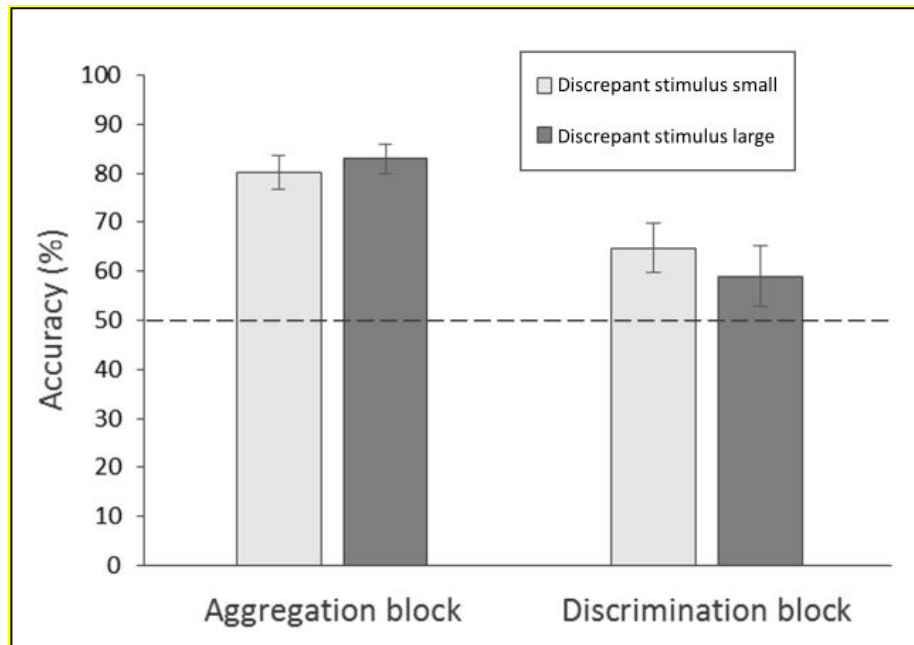


Figure 3. Accuracy in the Aggregation/Discrimination blocks in Experiment 1. Participants' performance was significantly higher in the Aggregation block compared to the Discrimination block. Accurate judgement of total intensity was possible even if discrimination of the overall discrepancy between the stimuli was just slightly above chance level. The dashed line represents the chance level (50%). Error bars show standard error of the mean.

Next, we tested whether the intensity of each single event in a discrepant pair could be retrieved even when participants' attention was mainly directed toward the global features of the percept (i.e. overall intensity or overall discrepancy). To this purpose, we run a 2 (judgement: aggregation/discrimination) x 2 (total intensity: small/large) x 2 (event intensity: weak/strong) repeated measures ANOVA on participants' magnitude estimation in the rating trials. We found no main effect of judgement ($F(1, 15) = 0.086$;

$p = 0.774$), but a significant main effect of total intensity ($F(1, 15) = 13.476$; $p = 0.002$; $\eta^2 = 0.473$) and event intensity ($F(1, 15) = 65.352$; $p < 0.001$; $\eta^2 = 0.813$). No interaction was significant (all $p > 0.077$). Overall, large totals induced higher magnitude estimation ratings (mean \pm SD: 5.639 ± 0.273) than small totals (mean \pm SD: 4.498 ± 0.209). Moreover, regardless of the block and the total intensity, the strong event in the pair was rated as greater (mean \pm SD: 6.879 ± 0.254) than the weak stimulus (mean \pm SD: 3.256 ± 0.325) (see Figure 4). Thus, participants were equally accurate in perceiving the intensity of single events when the context required them to focus primarily on discrepancies or totals of stimulus pairs. Put another way, information about the intensity of individual components was not lost when participants attended to total intensity.

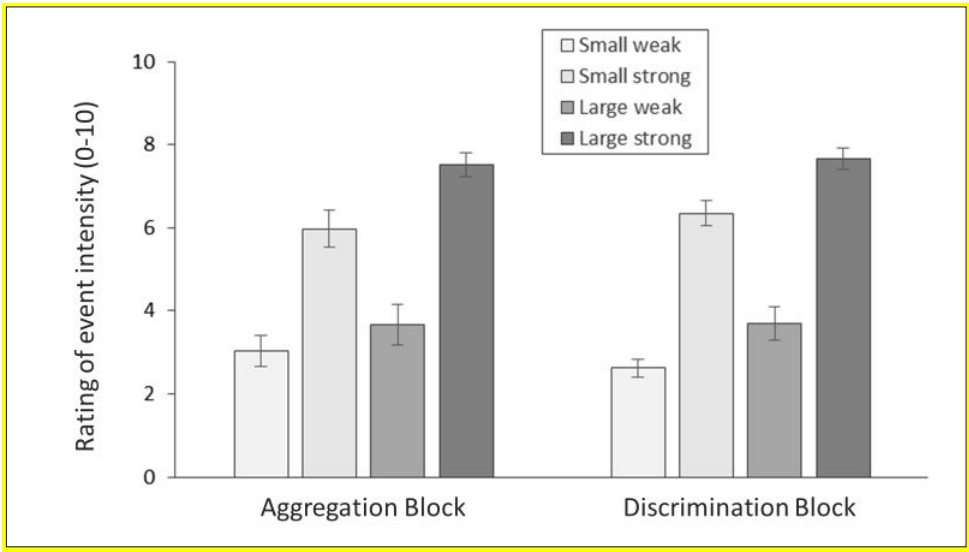


Figure 4. Magnitude estimate of single events in the rating trials presented in Experiment 1. Participants showed accurate perception of the intensity of each stimulus (weak/strong event, small/large total) in both the Aggregation and the Discrimination block. Error bars show standard error of the mean.

Experiment 2

We tested whether our results replicated the nonlinear overestimation bias described by Walsh and colleagues (2016). A 2 (total intensity: small/large) x 3 (discrepancy: 0%, 70%, or 100%) repeated measures ANOVA was applied to participants' performance in each condition (see Figure 5a). When the data violated the assumption of sphericity, a Greenhouse-Geisser correction was applied. The analysis revealed no significant effect of total intensity ($F(1, 19) = 0.196; p = 0.663$), but a significant main effect of discrepancy ($F(1.5, 28.8) = 6.509; p = 0.008; \eta^2 = 0.255$). Pairwise comparisons between each level of discrepancy showed that accuracy was significantly lower in the 100% discrepant condition compared to 70% discrepant condition (mean difference: $-6.650; p = 0.021$; CI $-12.182, -1.118$) and 0% discrepant condition (mean difference: $-11.411; p = 0.010$; CI $-19.73, -3.091$). The interaction between total intensity and discrepancy was also significant ($F(1.3, 24.9) = 20.189; p < 0.001; \eta^2 = 0.515$). Pairwise comparisons showed that all discrepancy conditions were significantly different from each other in the small total ($p < 0.001$ in all cases), but not in the large total ($p > 0.232$ in all the cases). Finally, a significant difference between the totals was found both in the 0% and the 100% discrepant condition ($p < 0.014$ in both cases) (see Figure 5a). Overall, participants' accuracy in total intensity judgements significantly decreased as discrepancy increased. Thus, participants showed a systematic overestimation error in judging the total of discrepant stimuli.

Next, we used a **Signal Detection Theory (SDT)** approach to investigate whether such overestimation bias was due to a genuine perceptual process and/or to a change in **perceptual bias**. We arbitrarily defined a hit as a "large" response when the large total was presented, and a false alarm as a "large" response when the small total was delivered. Sensory discriminability (d'), calculated as $z(pHIT) - z(pFA)$ **perceptual bias (B)**, calculated as $0.5 * [z(pHIT) + z(pFA)]$, were then estimated from the hit rate and false

alarm rate. First, to compare the perceptual discriminability of double tactile stimulations at increasing levels of discrepancy (discrepancy: 0%, 70%, and 100%), we performed a one-way repeated measures ANOVA on participants' d' values. Data violated the assumption of sphericity, therefore Greenhouse-Geisser correction was applied. Discrepancy produced a significant effect on participants' sensitivity (d') ($F(1.5, 29) = 5.446$; $p = 0.015$; $\eta^2 = 0.223$). Pairwise comparisons showed that participants' sensitivity was significantly higher in the 0% discrepancy condition (mean \pm SD: 2.026 ± 0.86) compared to both the 70% (mean \pm SD: 1.614 ± 0.76 ; $p = 0.029$) and 100% (mean \pm SD: 1.472 ± 0.66 ; $p = 0.017$) discrepancy condition (see Figure 5b). Second, we ran another one-way repeated measures ANOVA on the participants' perceptual bias (B) comparing the three levels of discrepancy. Although many SDT paradigms cannot distinguish between perceptual and decision-based biases (Witt et al., 2015), in our task participants could not have a decision-based bias, because the different conditions were presented in a completely random fashion. Therefore, we believe we can safely interpret our results as a case of perceptual bias. Again, analyses were Greenhouse-Geisser corrected. The effect of discrepancy was highly significant ($F(1.3, 25) = 60.907$; $p < 0.001$; $\eta^2 = 0.762$). Pairwise comparisons showed that as discrepancy increased, participants' perceptual bias significantly shifted, producing a higher number of "large" responses ($p < 0.001$ in all comparison) (0% discrepancy condition, mean \pm SD: 0.522 ± 0.42 ; 70% discrepancy, mean \pm SD: -0.17 ± 0.38 ; 100% discrepancy, mean \pm SD: -0.432 ± 0.42) (see Figure 5c). Thus, as discrepancy between the two single intensities increased, the sensitivity to total intensity decreased and participants tended to perceive every stimulation as a large total (i.e. overestimation bias), regardless of the actual total stimulus intensity.

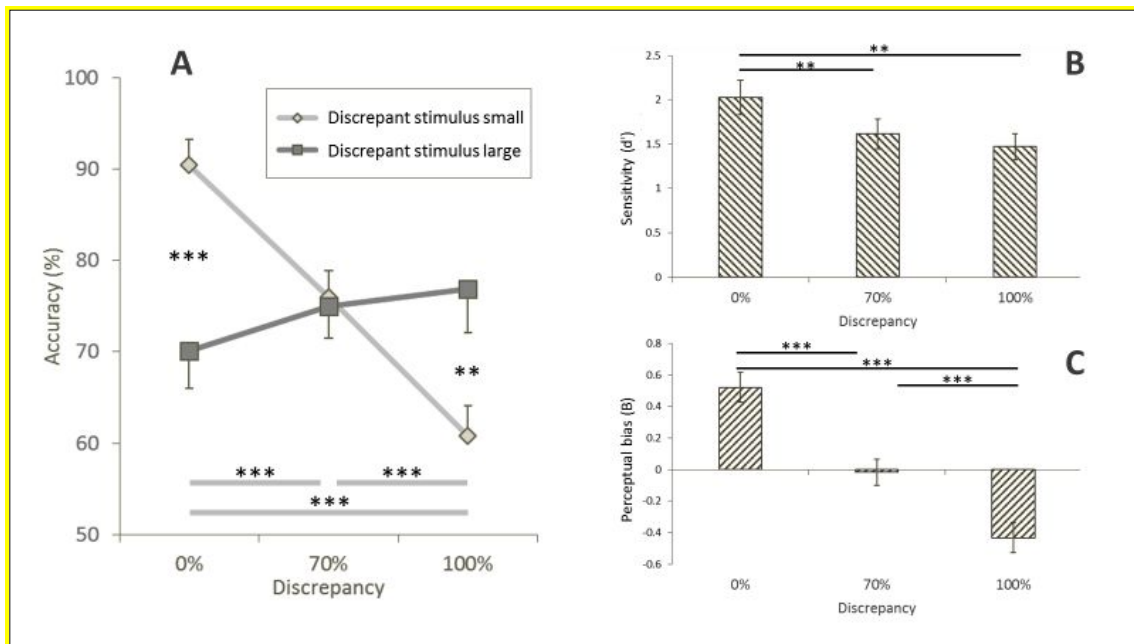


Figure 5. Accuracy, sensitivity, and perceptual bias along discrepancy in Experiment 2. Participants' accuracy (A) decreased along with discrepancy when the discrepant pair had a small total intensity, but not when the discrepant stimulus had a large total intensity. Both sensitivity (B) and perceptual bias (C) were significantly modulated by the discrepancy between the two simultaneous stimuli in the pair. Error bars show standard error of the mean.

Experiment 3

First, as a sanity check for the psychophysical method, we tested whether the results from low- and high-starting staircases converged to similar values. Paired t-tests analyses showed no statistical difference between both measurements in each condition ($p > 0.110$ in all comparisons), confirming convergence of the two staircases.

Hence, the values from ascending and descending staircases were averaged together and analysed in a 2 (number of stimuli: single/double) \times 2 (intensity: small/large) repeated measures ANOVA to evaluate any difference in perceived intensity among the four experimental conditions. We found a significant main effect of intensity ($F(1, 9) = 10.638$; $p = 0.010$; $\eta^2 = 0.542$), but no effect of number of stimuli ($F(1, 9) = 1.758$; $p =$

0.218) nor interaction between the factors ($F(1, 9) = 0.468$; $p = 0.511$). In particular, regardless of the number of fingers stimulated (one or two), participants reported a higher perceived total intensity when a large stimulus was present in the stimulation (mean \pm SD: 6.464 ± 2.04) compared to when the single/double stimulation was composed by the small stimulus/i only (mean \pm SD: 5.738 ± 1.98) (Figure 6). To check whether our non-significant results were due to a lack of statistical power, we conducted a post hoc power analysis using GPower (Faul & Erdfelder, 1992; Erdfelder, Faul, & Buchner, 1996) with power ($1 - \beta$) set at 0.80 and $\alpha = 0.05$. This showed us that sample size would have to increase up to $n = 46$, far beyond the range of the sample sizes used in previous studies (e.g., Walsh et al., 2016: $n = 10-16$) in order for the main effect of number of stimuli to reach statistical significance at the .05 level. Thus, it seems unlikely that our negative result was due to a limited sample size. Finally, non-significant result was further investigated through a Bayesian analysis, using JASP (version 0.9.2.0; JASP Team 2016, University of Amsterdam) to determine whether results supported the null hypothesis, or could alternatively reflect insufficient statistical power (Rouder et al., 2009; Wetzels, Grasman, & Wagenmakers, 2012). We found that the data about number of stimuli were 2.6 times more likely under the null hypothesis than the alternative hypothesis ($BF_{01} = 2.591$, error = 1.348%), suggesting that the absence of difference between single and double stimuli conditions was not simply due to a lack of statistical power.

Therefore, rather than relying on the actual (physical) total intensity, participants' perception was strongly influenced by the most salient stimulus in the pair only.

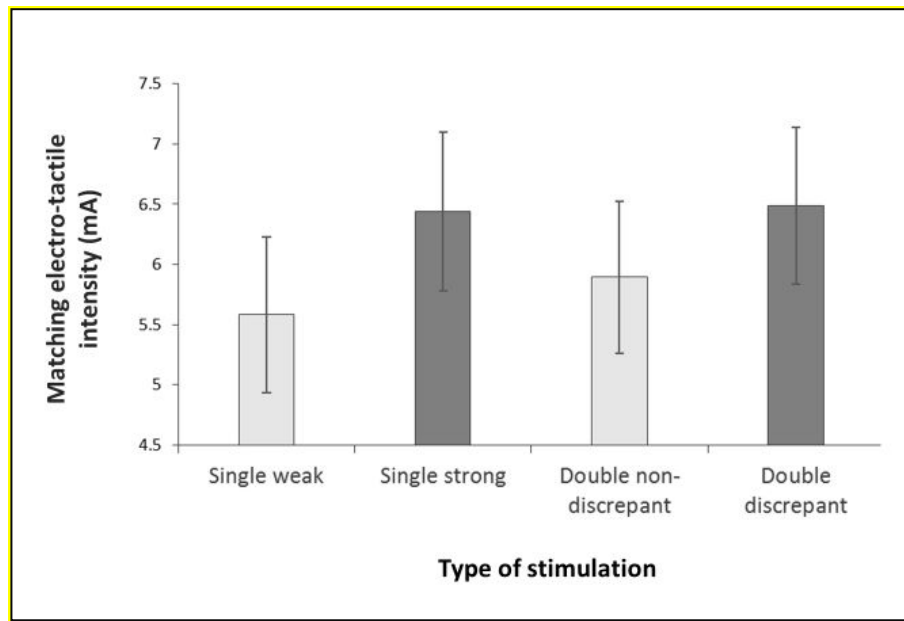


Figure 6. Matching electro-tactile intensity of single/double weak/strong stimuli in Experiment 3. Participants perceived a larger total intensity when a strong stimulus was present in the stimulation, compared to when the single or double stimulation was composed by the small stimulus/i, suggesting that the perception of double discrepant stimulation is strongly biased towards the more salient stimulus in the pair.

Discussion

The sense of touch must deal with multiple, highly diverse stimuli impinging simultaneously on the cutaneous receptors. Psychology of perception has classically studied touch through the presentation of artificially isolated events. The question of why some components of total tactile stimulation are perceptually dominant, while others are neglected, has rarely been addressed. Most discussions invoke peripheral or central adaptation, selective attention, and low bandwidth of tactile perception (see Gallace & Spence, 2014 for a review). Here we investigated the mechanisms underlying the somatosensory integration of double discrepant electro-tactile stimuli.

Across three experiments, we replicated and extended previous findings of nonlinear aggregation of multiple tactile intensities (Walsh et al., 2016). Those authors

suggested that perception of total tactile intensity involves a salience-based overestimation bias: the strongest component stimulus has a disproportionate weighting in the perception of the total. Our study adds several new pieces of knowledge. First, in Experiment 1 we showed that (1) the intensity of each component event in a double stimulation can be correctly perceived (rating trials), and yet, (2) somatosensory aggregation does not rely on the prior discrimination and separate perception of the intensity of each independent stimulus component, followed by the simple summation of those components. Rather perception of total intensity appears to involve specific processes that occur in addition to the perception and summation of individual component stimuli. Second, in Experiment 2 we extended the results on the overestimation bias described by Walsh and colleagues (2016), using a different psychophysical approach. We found that participants' accuracy in judging the total intensity of increasingly discrepant pairs significantly decreased when the total was small, but not when the total was large, confirming the unidirectionality of the overestimation effect found by Walsh et al. (2016). Small discrepant totals were (mis-)perceived as larger than reality, while large totals were not affected or, if anything, were also felt as larger than their physical intensity. Importantly, we also found that sensitivity to overall intensity significantly decreases as the discrepancy between two events in a tactile percept increases, thus increasing the probability of perceiving the total as larger than its actual physical intensity. Last, in Experiment 3, we quantified the extent to which the intensity of a single strong stimulus contributes to the perception of the overall intensity of a discrepant pair, showing that judgements of total intensity of multiple stimulations strongly rely on the intensity of the most salient stimulus in the percept.

Perception of the single events forming a total tactile percept

Results in Experiment 1 showed that participants accurately perceived intensity of each component in a discrepant double tactile stimulation. Thus, judging the properties of the whole percept (i.e. overall intensity or overall discrepancy) did not affect perception and retrieval of information about the parts. This is in apparent contrast with previous reports about holistic perception in other sensory modalities (Nelson, 1993). Poljac and colleagues (2012), for example, reported that the ability to detect colour changes in a pattern of scrambled dots dramatically drops when the dots can be integrated into a meaningful Gestalt, suggesting that the construction of a visual whole comes at the cost of reduced access to information about its constituent parts. Similarly, Mathis and Kahan (2014) showed that the holistic perception of Kanizsa figures reduces the identification of local-level elements such as edges. Auditory studies (Wile & Balaban, 2007; Schneider & Wengenroth, 2009) suggest that the perception of a holistic virtual pitch (an illusory tone derived by the nonlinear integration of multiple simultaneous pure tones) prevents the detection of changes in some of its components, giving rise to several illusory phenomena such as the *Shepard scale illusion* (Shepard, 1964), the *phantom fundamental* (Turner, 1977), and the *tritone paradox* (Deutsch, 1986). Although still in debate (Nelson, 1993; Cacciamani et al., 2014), these findings are often quoted as evidence that when stimuli are processed as integrated wholes, access to the component parts is lost or reduced.

Increasing evidence suggests that grouping of multiple stimuli in a unitary Gestalt can also occur for somatosensory stimuli (Kitagawa et al., 2009; Chang et al., 2007; Carter et al., 2008; Serino et al., 2008; for a review see Gallace & Spence, 2011). However, to our knowledge this is the first attempt to investigate how the properties of a tactile whole relate to the perception of its parts. In Experiment 1 (rating trials), we unpredictably asked participants to report the intensity of a single event while they

performed a task requiring perception of multiple stimuli (overall intensity/discrepancy). An account of somatosensory integration based on the effects described above for visual and auditory modalities would predict that judging a compound tactile stimulus for either total intensity or discrepancy, should produce the loss of specific information regarding each individual component. However, participants remained accurate in magnitude estimations of single stimuli in Experiment 1. This demonstrates that the perception of the single stimuli was not affected by the holistic judgements required by the main tasks.

A crucial difference between our paradigm and the studies above (Poljac et al., 2012; Mathis and Kahan, 2014) is that our whole/part judgements were given in separate trials, rather than together. This might have potentially brought to a situation in which participants switched very rapidly from a “holistic mode” to an “analytic mode” (Foard, and Nelson, 1984), instead of processing the information in parallel. Yet, such a possibility seems unlikely for at least **three** reasons. First, rating trials were significantly rarer than main trials in Experiment 1. Therefore, it seems quite reasonable to assume that participants maintained a “holistic mode” during the entire course of each block, as a strategy based on attending to both tasks simultaneously would have been overly slow and effortful. Second, **the rating trials occurred in a completely unpredictable fashion throughout the experiment, and participants were not informed about the type of trial until its very presentation. Thus, it was virtually impossible for the participants to adjust their strategy in function of the type of trial.** Finally, studies using the *global-local task* in visual perception (Navon, 1977; Kimchi, 1992; for a review, see Kimchi, 2015) show that global features have precedence over local features, such that perception of the whole typically recruits attentional resources more readily and automatically than perception of the constituent parts (but see also Davidoff et al., 2008).

Thus, our results suggest that the intensity of single stimuli in a tactile whole can be successfully retrieved in spite of the fact that attention is directed towards the global characteristics of the percept. The somatosensory system may be relatively exempt from the ‘global dominates local’ phenomena in other sensory modalities. Importantly, therefore, information about individual component stimuli could remain available for further computations, such as the estimation of the salience of each stimulus in the percept.

Aggregation versus discrimination of multiple stimuli

Perception of total intensity could rely on two alternative processes. One possibility is that aggregation involves first perceiving each individual stimulus, and subsequently summing all the individual components. Alternatively, aggregation of intensity could rely on a specific module, independent from the precise discrimination of single events. Previous results suggest that this module would be strongly influenced by the salience of stimuli (Walsh et al., 2016).

On the first account, information about single intensities is indeed available (as suggested by rating trials in Experiment 1). Therefore, a simple comparison could compute the discrepancy between one stimulus and another. On this view, the discrepancy between any pair of inputs should remain available for report. Yet, our results from the discrimination block in Experiment 1 showed that discrepancy perception was surprisingly poor, even when information about individual component intensities was fully processed (as shown by rating trials). The comparative information about the difference between their intensities was either lacking or inaccessible to perceptual awareness.

Conversely, results from the aggregation block (Experiment 1) show that the total intensity of a tactile stimulation was above 80% even if the single parts composing it could not be separated and discriminated equally well (~60% accuracy). This finding clearly supports the idea that somatosensory aggregation occurs automatically and without requiring individuated perception of each component. Therefore, total intensity of multiple inputs must be computed through perceptual mechanisms of weighted summation which are independent from the perceptual individuation of component stimuli, yet are related to their relative intensities.

Our result indicates that the intensity of two simultaneous events is poorly discriminated. This is in line with previous studies investigating masking tasks (Craig, 1976; von Békésy, 1967) and double simultaneous stimulation tasks (Sherrick, 1964; Tamè, Farnè, & Pavani, 2011). In such paradigms, the *detection* of a tactile event drastically deteriorates when the stimulus is presented in spatial and temporal proximity with a distractor. Even though in our task participants were asked to judge the *intensity* of the single events, rather than simply detecting the stimuli, it is possible that the same mechanisms of competition and limited sensory bandwidth described for masking and DSS are responsible for the relatively low accuracy in this task. In contrast, our finding that the same double simultaneous stimuli are more accurately aggregated than discriminated is entirely novel for at least two reasons. First, while an ever-increasing number of studies focus on the integrative effects taking place between different sensory modalities (e.g. Redundant Target Effect, Foster et al., 2002; Crossmodal Congruency Effect, Spence, Pavani, Maravita, & Holmes, 2008), our aggregation task required the integration of multiple *unimodal* (i.e. purely tactile) stimuli. Second, while most of the paradigms mentioned above are based on reaction times and stimulus detection, in our task, participants were instead asked to judge the *total intensity* of multiple touches.

Memory for somatosensory stimuli is reportedly very short, lasting for about 700ms (Harris et al., 2002). However, in the two-alternative forced choices paradigm used in Experiment 1 there was a 1s interval between the first and the second pair of stimuli. Therefore, one may argue that an alternative explanation for participants' scarce accuracy in discrepancy detection might be ascribed to limited mnemonic resources. Although our data cannot entirely rule out this possibility, it is important to note that the same 1s delay was present in the aggregation block, where participants showed significantly higher performance. Our results show a distinctive limitation of tactile information-processing in comparing two distinct simultaneous sensations, even under circumstances where those sensations can be successfully aggregated. This finding is consistent with the low bandwidth or perceptual capacity reported for touch (Gallace & Spence, 2014).

Mechanisms underlying overestimation of multiple discrepant stimuli

In line with Walsh and colleagues (2016), our findings from Experiment 2 show a characteristic error in aggregation of multiple somatosensory stimulation. The total intensity of discrepant stimuli is systematically overestimated. Walsh and colleagues (2016) proposed that the overestimation of discrepant stimuli is driven by a perceptual peak-bias mechanism relying on the salience of each stimulus. However, such a hypothesis was not yet properly supported by a model describing how salience is first computed, and then used in subsequent weighted summation.

First, one might ask whether overestimation of discrepant intensities reflects an inherent property of the somatosensory system, or is rather a cognitive strategy. Peak-biased judgements have been described in social, affective, and cognitive psychology for a variety of situations (Carmon & Kahneman, 1996; Morewedge, Gilber, & Wilson, 2005;

Kemp, Burt, & Furneaux, 2008). We used a signal-detection paradigm to dissociate perceptual sensitivity to total stimulation intensity from decision biases (Green & Sweets, 1996). We found that as the discrepancy between the two stimuli increased, participants' sensitivity to total intensity decreased significantly. That is, discrepant pairs were perceived as more intense than non-discrepant pairs having the same total intensity. Interestingly, the decrease in d' was accompanied by a significant change in perceptual bias. Participants perception of the small/large totals significantly shifted as discrepancy increased, inducing participants to judge all double stimulations as 'large', irrespective of their actual total intensity.

Thus, Experiment 2 suggests that overestimation of discrepant intensities depends on a genuinely perceptual process. Yet, it still remains unclear what kind of sensory mechanism could lead to such a supra-additive effect. Nonlinear interactions between multiple unimodal somatosensory stimuli have been previously described. However, they traditionally refer to sub-additive phenomena attributable to lateral inhibition. Lateral inhibition is a well-known form of interaction between multiple somatosensory stimuli (von Békésy, 1967; DiCarlo & Johnson, 1999, 2000; DiCarlo, Johnson, & Hsiao, 1998). This mechanism tends to suppress the response to a stimulus when another, nearby region of the receptor surface is strongly stimulated. Therefore, lateral inhibition increases contrast sensitivity and sharpens tactile discrimination between multiple simultaneous stimuli: only the strongest signal is available for further analysis, while the surrounding signals are damped.

Our results from Experiment 3 are consistent with a strong effect of lateral inhibition: adding an additional stimulus did not significantly increase perceived total intensity. However, lateral inhibition alone appears unable to account for the overestimation of discrepant stimuli, since discrepant pairs were perceived as larger than

equally-intense non-discrepant pairs (see also Walsh et al., 2016). In other words, lateral inhibition might reduce, but should never boost, total perception, therefore an additional process is needed to explain our overestimation result.

Figure 7 schematically depicts a scenario for comparing the total intensity of two different tactile pairs. Crucially, as in our task, the overall physical intensity of the two pairs is comparable. Within each pair, however, the distribution across the fingers varies, providing non-discrepant (A) or discrepant (B) conditions.

First, when two stimuli (x_1 and x_2) are simultaneously delivered on adjacent fingers, lateral inhibition produces a mutual reduction of both signals. The effect of this inhibition on each individual digit (l_i) is assumed to depend on the stimulation of the fingers adjacent to it:

$$l_i = (x_{i-1} + x_{i+1}) \cdot c$$

Thus, for each finger (i), the sum of the physical intensity delivered to the fingers adjacent to it (x_{i-1} , x_{i+1}) is multiplied by a constant value (c). For non-discrepant stimulus pairs, lateral inhibition affects both component stimuli equally. In contrast, for discrepant pairs, the stronger stimulus will produce a stronger inhibition on the weaker stimulus, and will itself be less inhibited by the weaker stimulus. **Importantly, given that lateral inhibition linearly depends on the intensity of the two adjacent fingers, if the same overall intensity is redistributed across fingers, then the overall lateral inhibition is also invariant.** That is, lateral inhibition enhances discrepancies between individual component stimuli, but, other things being equal, has no net effect on total intensity.

The rating trials from Experiment 1 show that, at this stage, the intensity of each event in the discrepant pair (B) can be correctly detected and reported. Importantly, results from our Experiment 3 provide a direct measure of the parameter c . Comparing

the perceived intensity of a single stimulus with its double, non-discrepant version, we found that the latter was perceived only slightly (and non-significantly) larger than the former. This suggests that our paradigm produced strong lateral inhibition. We estimated the value of c in our data using a version of the interaction ratio (Ruben et al., 2006; Hsieh et al., 1995). This measure of lateral inhibition computes the normalised difference between the perceived intensity of a double stimulation and the linear summation of each single event:

$$c = \frac{[perceived\ int(x_1) + perceived\ int(x_2)] - perceived\ overall\ int}{[perceived\ int(x_1) + perceived\ int(x_2)]}$$

In particular, in line with previous results (Ruben et al., 2006) in our data from Experiment 3, c was 0.46 ± 0.07 SD.

At the second stage of somatosensory integration, the *salience* of each stimulus is computed, and then forwarded to the next module, for the appropriate weighted summation. We suggest that the *salience* of each event (w_i) is calculated after the lateral inhibition stage, as a function of the ratio between each single event and the average intensity of all the concurrent stimulations.

$$w_i = \frac{x_i}{\overline{X}}$$

On this view, a salient signal is one that stands out from the average intensity of concurrent, irrelevant, stimulations (noise). According to this definition, in the case of the non-discrepant pair, the weighting factor for each stimulus will obviously be always equal to one. Crucially, in the case of the discrepant pair, instead, the stronger stimulus

will receive a weight above unity. This effectively amplifies the intensity of this component, and biases the perception of the whole percept.

Finally, in a third stage, the estimation of the overall intensity of each pair can be computed according to:

$$\hat{I} = \sum_{i=1}^n (x_i - l_i) \cdot w_i$$

where the physical intensity of each event x_i – net of its corresponding lateral inhibition value l_i – is multiplied by its respective weight w_i and summed across all components of the total stimulation.

Our model of salience detection is coherent with the classical neural model of *divisive normalisation* (Carandini & Heeger, 2011; Heeger, 1992; Carandini, Heeger, & Movshon, 1997). According to the divisive normalisation model, the initial input-driven activity of a neuron is divided by the summed activity of a large pool of neighbouring neurons (Louie, Khaw, & Glimcher, 2013). Divisive normalisation has proven to be a useful model to explain nonlinear responses in the visual (Heeger, 1991, 1992; Albrecht, & Geisler, 1991), olfactory (Olsen, Bhandawat, & Wilson, 2010), and auditory system (Rabinowitz, Willmore, Schnupp, & King, 2011; David, Mesgarani, Fritz, & Shamma, 2009), as well as multisensory (Ohshiro, Angelaki, & DeAngelis, 2011) and even cognitive processes (Louie, Khaw, & Glimcher, 2013; Louie Grattan, & Glimcher, 2011; Reynolds & Heeger, 2009). Although the divisive normalisation model has been classically interpreted as a canonical mechanism for maximising sensitivity (Brouwer, Arnedo, Offen, Heeger, & Grant, 2015) and reducing redundancy (Sinz & Bethge, 2013), our results suggest it could also contribute to perceptual aggregation of multi-component stimuli.

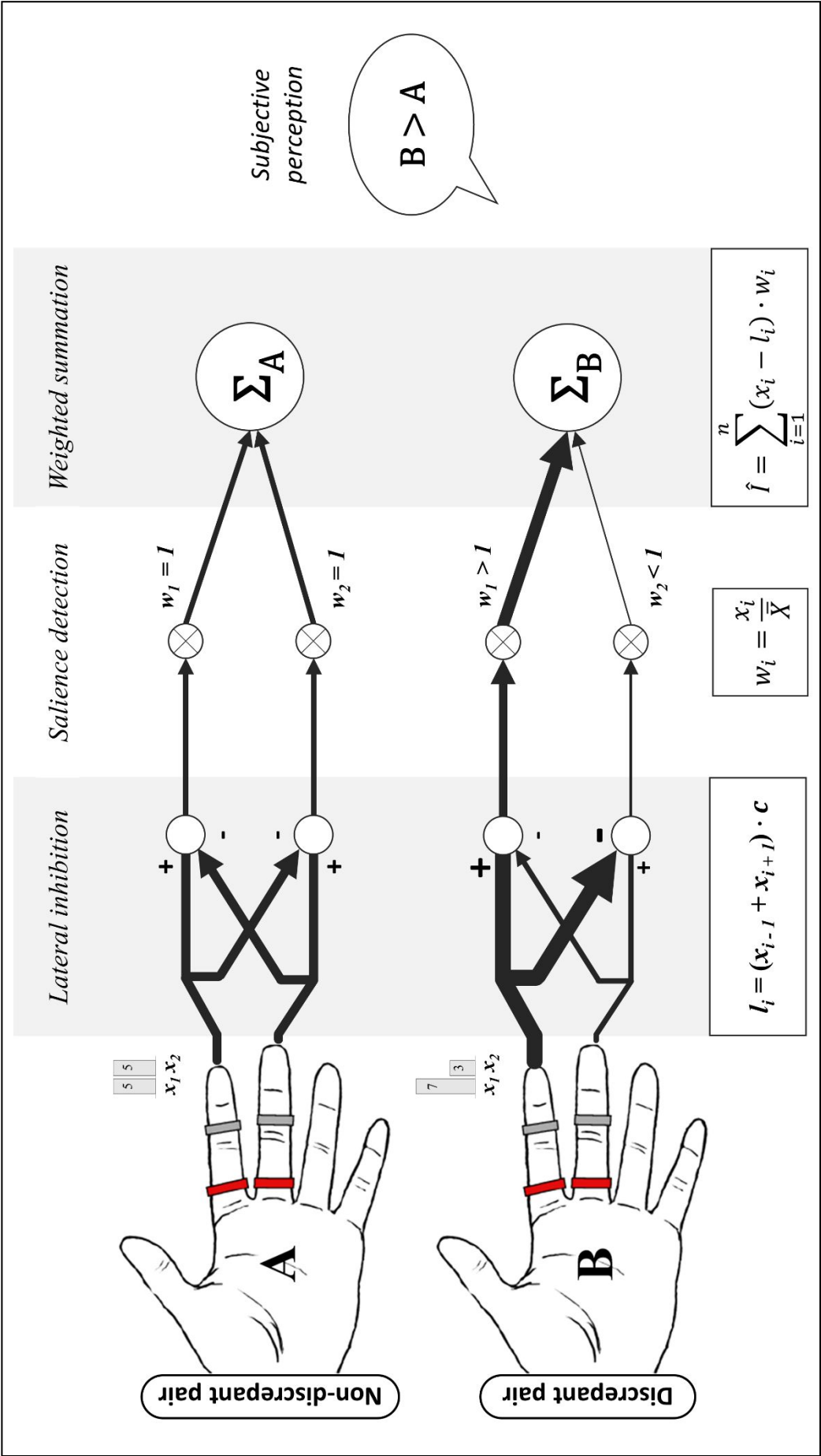


Figure 7. Putative model of somatosensory integration of multiple discrepant and non-discrepant stimuli. A. When non-discrepant multiple simultaneous somatosensory stimuli are aggregated in a total percept, the physical intensity delivered to each finger (i) is first reduced by lateral inhibition (l_i) (top left of the scheme). Experiment 1 shows that at this stage, the intensity of each input after lateral inhibition is retrievable. Next, in non-discrepant pairs, the salience value is the same for both stimuli. Therefore, the weight assigned to each stimulus (w_i) is 1 (top centre of the scheme), and the weighted summation of the events only reflects the sub-additive effect of lateral inhibition (top right of the scheme). B. Multiple discrepant stimuli are also subject to lateral inhibition from the adjacent fingers. However, the amount of lateral inhibition is different among the stimuli, with the weak stimuli producing less inhibition of the strong stimuli (bottom left of the scheme). Single stimulus intensity of discrepant patterns after lateral inhibition is also accessible. Next, as the strong stimulus is larger than the average intensity of the multiple stimulation, the weight assigned to it is > 1 , while the weight of the weak stimulus is < 1 (bottom centre of the scheme). Finally, the weighted summation of the discrepant pair is biased towards the strong stimulus in the pattern (bottom right of the scheme). As a result, the comparison between equally-intense non-discrepant and discrepant pairs produces an overestimation of the discrepant pattern, driven by the salience of the strongest stimulus (far right of the scheme).

Interestingly, a recent fMRI study used *divisive normalisation* models to explain the suppression of somatosensory responses during concurrent stimulations of different digits (Brouwer, Arnedo, Offen, Heeger, & Grant, 2015). In particular, Brouwer and colleagues (2015) speculated that interdigit suppression (i.e. lateral inhibition) may be evident in the subregions of S1 in which each neuron responds to only one digit, while normalization is stronger in subregions of S1 that have neurons with larger receptive fields encompassing more than one digit (Krause et al., 2001; Besle et al. 2013, 2014).

All our experiments involved simultaneous double stimulation. Different salience mechanisms apply when processing a series of stimuli. For example, in oddball tasks (Squires, Squires, & Hillyard, 1975; Halgren, Marinkovic, & Chauvel, 1998), the oddball is salient because it deviates from a predictive model learned from previous stimuli. Such effects can also be described as a form of central adaptation. In principle, divisive normalization mechanisms for simultaneous stimuli might interact with central adaptation mechanisms. For example, Tamè and colleagues (2015) have shown that lateral

inhibition is responsible for a strong repetition suppression (i.e. a decrement of neuronal responses for repeated presentation of a stimulus) during simultaneous tactile stimulation of non-homologous fingers. In contrast, neural adaptation accounts for repetition suppression effects for consecutive stimuli delivered to homologous fingers. Thus, several mechanisms, both spatial and temporal, may contribute to salience, but our investigation focusses particularly on lateral inhibition between simultaneous stimuli.

Simulations

We ran two separate simulations to test our salience model against a model based on lateral inhibition only and against the actual data from Experiment 2 and 3, respectively.

Model comparison between the salience model and the lateral inhibition model in Experiment 2

First, we used the formula for our salience model

$$\hat{I} = \sum_{i=1}^n (x_i - l_i) \cdot w_i$$

to estimate each participants' perceived total intensity (\hat{I}) in each condition of Experiment 2. For each individual participant, we fed the model with each stimulus intensity (x_i) constituting either the small or the large totals along the three levels of discrepancy (0%, 70%, and 100%). Similarly, we estimated participants' perception as predicted by a lateral inhibition model by simply removing the salience weighting parameter (w_i) from our original formula, thus obtaining:

$$\hat{I} = \sum_{i=1}^n (x_i - l_i)$$

Then, to compare the output of either model with the experimental data from Experiment 2, we converted both measures into percentage change (in accuracy for performance data, or perceived intensity for model predictions) between each discrepant condition (70% and 100%) and the non-discrepant condition (0% discrepancy: baseline). That is, we computed $\Delta\%(\text{condition}) = (\text{condition} - \text{baseline}) / \text{baseline}$. This captures the fact that larger discrepancies should have greater effects on perception of the average. Figure 8 shows the percentage change for each total (small/large) in the experimental data and both models.

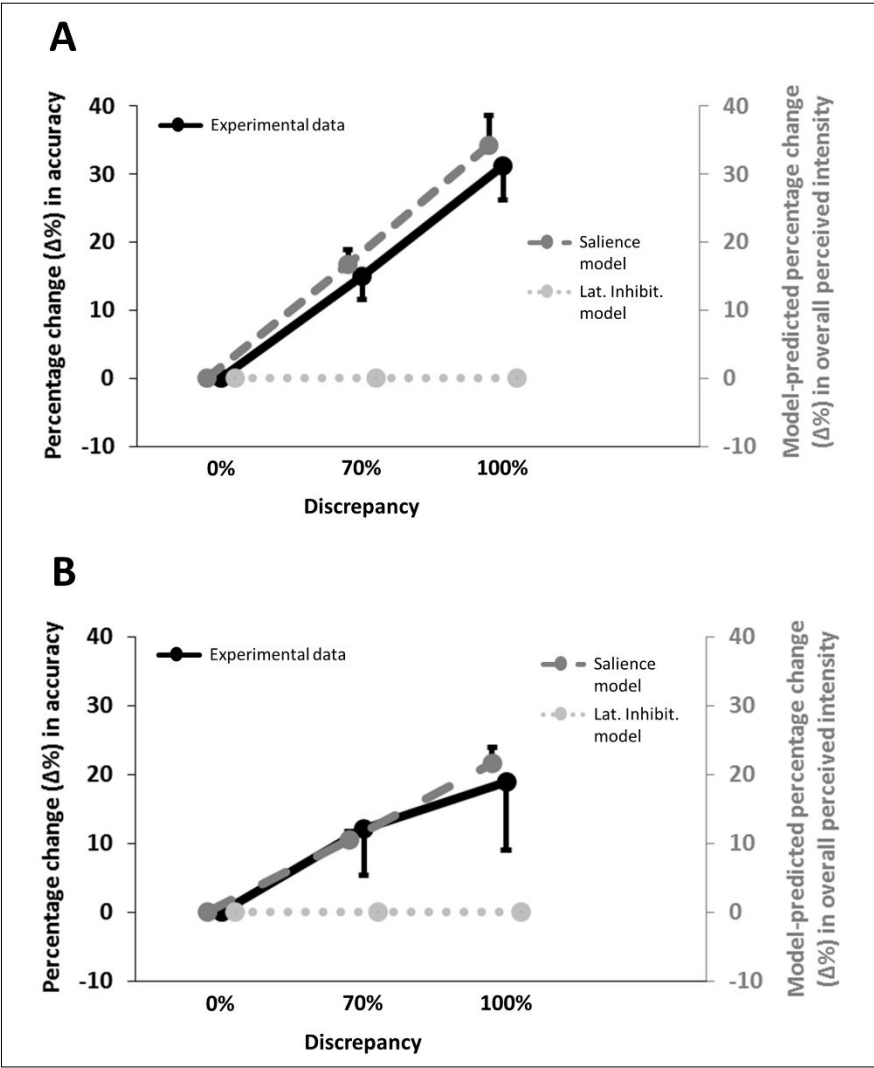


Figure 8. Actual and predicted percentage change between the non-discrepant condition (0%) and the two discrepant conditions in Experiment 2 (70%, 100%) for the small (A) and the large (B) totals. Experimental data (black line) are referred to the left Y axis, and perceived intensities predicted by the models (grey lines) are referred to the right Y axis. The lateral inhibition model (dotted grey line) predicts no change in perception of overall intensity as a function of discrepancy. Error bars show standard error of the mean.

To evaluate the models shown in figure 8, we used Akaike Information Criterion (AIC) (Akaike, 1973, 1978; Bozdogan, 1987), following the procedures of Wagenmakers & Farrell (2004). Briefly, we first calculated the AIC values for each model, using the small-sample correction value AICc (Burnham & Anderson, 2002). We then computed $\Delta(\text{AICc})$, as the difference between the AICc score of each model minus that of the best

model, and the Akaike weights, $w(\text{AICc})$, as the normalised probability of each model being the best model given the data and the set of candidate models (with the sum of all weights of the set being equal to 1). Finally, we calculated an evidence ratio by converting these probabilities to odds.

Table 1 shows the AIC results for the salience model and the lateral inhibition model, for the small and large total intensities. The evidence ratio (defined as the ratio between the Akaike weights of one model over the other) showed that the salience model was 1.66×10^7 times more likely than the lateral inhibition model in fitting the data for the smaller total intensity, and 5.84 times more likely for the large total.

<i>Model</i>	<i>No. Par</i>	<i>AIC</i>	<i>AICc</i>	<i>$\Delta(\text{AICc})$</i>	<i>$w(\text{AICc})$</i>	<i>ER</i>
<i>Small total</i>						
Salience model	1	355.06	355.13	0	> 0.999	1.66×10^7
Lateral inhibition	1	388.31	388.38	33.24	< 0.001	
<i>Large total</i>						
Salience model	1	417.73	417.80	0	0.85	5.84
Lateral inhibition	1	421.26	421.33	3.53	0.15	

Table 1. Results of the model comparison analysis using AIC to quantify the goodness of fit of the salience model vs. the lateral inhibition model for the small (top) and large (bottom) totals tested in Experiment 2.

Model comparison between the salience model and the lateral inhibition model in Experiment 3

In a second comparison analysis, we tested the goodness of fit of the salience model against the lateral inhibition model in fitting the data from Experiment 3. Again, we fed each model with the physical intensities delivered during of single/double, non-discrepant/discrepant stimuli. Then we computed the percentage change between the single weak stimulus condition and all the other conditions in both real and predicted data (see Figure 9). As expected, both models produced the same results for the double non-discrepant condition, where the two inputs have equal salience. However, the models

deeply diverged in the double discrepant condition. While the lateral inhibition model predicted the same total intensity for double discrepant and non-discrepant pairs, the salience model predicted an overestimation of the total intensity of the discrepant pair, due to a higher weighting of the strongest stimulus in the pair. Again, a model comparison analysis using AIC (see Table 2) strongly favoured the salience model showing that it was 104.4 times more likely than the lateral inhibition model.

Thus, a simple model of salience-based weighting was able to describe and explain overestimation of total intensity of double simultaneous stimulations at increasing level of discrepancy.

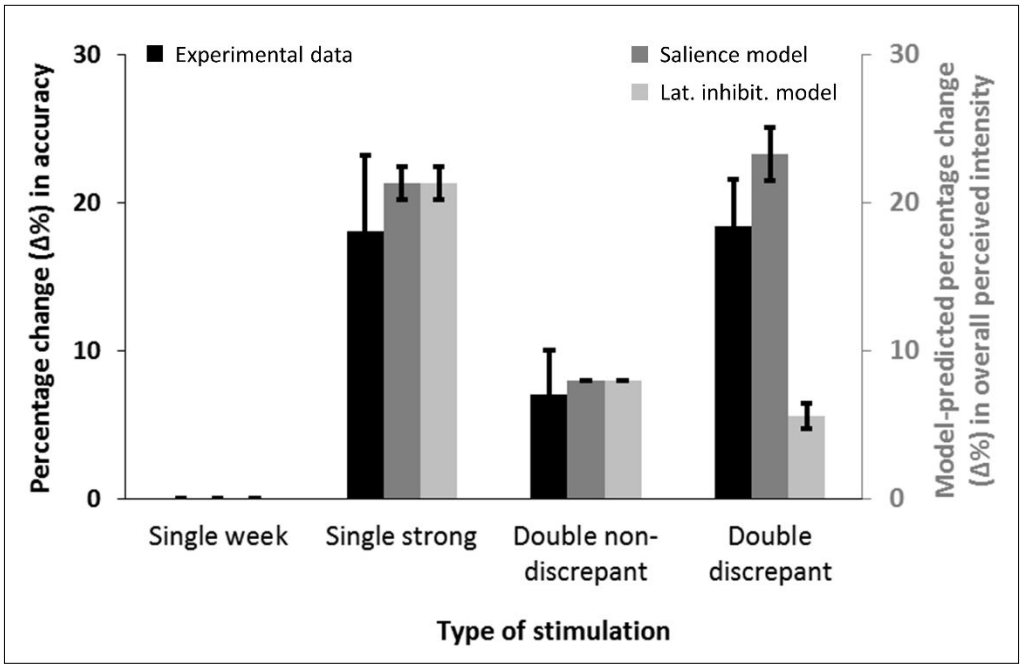


Figure 9. Actual and predicted percentage change between the single weak stimulus condition and the other conditions in Experiment 3 (single strong, double non-discrepant, double discrepant). Experimental data (black bar) are referred to the left Y axis, and predicted intensities (grey bars) are referred to the right Y axis. Both models predicted the same results for the double non-discrepant condition, where the two inputs had equal salience. However, the two models produced very different outcomes for the double discrepant condition, where one stimulus in the pair was more salient (was stronger than the average of the total stimulation). Note that model performance is consistent with the previous simulations of Experiment 2 (see Figure 8), where the lateral inhibition model predicted no change in perception of overall intensity at different levels of discrepancy. Here, the numerical difference between the non-discrepant and discrepant double

stimulations for the lateral inhibition model is due to the fact that the intensity of x_1 and x_2 in Experiment 3 were adjusted to be perceptually, rather than physically identical. Error bars show standard error of the mean.

<i>Model</i>	<i>No. Par</i>	<i>AIC</i>	<i>AICc</i>	$\Delta(AICc)$	$w(AICc)$	<i>ER</i>
Saliency model	1	208.87	208.98	0	0.99	104.4
Lateral inhibition	1	218.17	218.27	9.30	0.01	

Table 2. Results of the model comparison analysis on the conditions of Experiment 3. AICc weights strongly favoured the saliency model over the lateral inhibition model.

Saliency, attention and integration

We have assumed that the more intense stimulus of a pair is also the more salient. In general, physiological responses such as startle confirm that intense stimuli are, ipso facto, highly salient (Koch, 1999; Yeomans, Li, Scott, & Frankland, 2002; Davis, 1984; Landis & Hunt, 1939). In the psychological literature, however, saliency may be used in a different sense, to mean a stimulus that stands out from other, distractor stimuli. In this second sense, a less intense stimulus might potentially be salient within a field of more intense stimuli. Our study follows the first principle, namely that more intense stimuli are more salient than less intense stimuli. Intense stimuli attract attention and trigger orienting reactions, since they represent potential threats. In neuropsychology, saliency has typically been studied in the context of exogenous attention (Corbetta & Shulman, 2002), and is thought to trigger *selective* processing. For example, a sudden flash at a particular spatial location triggers attention, and gaze shifts, to *that* location. Our studies show that saliency also has important effects on non-selective, integrative processing, in this case the aggregation of component stimuli to form a common, overall percept. Interestingly, the effects of saliency on integrative processing are amplificatory, as also

are many effects of salience on selective processing. It remains unclear whether effects of salience on perceptual aggregation represent a failure of selectivity (e.g., a leakage of selection-based modulations of gain to surrounding stimuli), a non-specific effect of salience such as arousal, or a specific mechanism for enhancing processing stimuli that are both intense and spatially extensive (and perhaps therefore particularly threatening).

Given that our overestimation effect was clearly explained by a model involving divisive normalisation but not by a model involving lateral inhibition only, neural populations with multidigit receptive fields in Brodmann areas 1 and 2 (Krause et al., 2001) may underly our saliency-detection mechanism. In any event, our results suggest that the traditional focus in perceptual psychology on the link between salience and selectivity is only one aspect of saliency.

Conclusion

Our study sheds light on the cognitive processes underlying the integration of multiple simultaneous tactile stimuli to produce an overall percept. Despite the fact that such stimuli constitute the rule – rather than the exception – of our daily interactions with the environment, to our knowledge this is the first attempt to uncover the mechanisms behind the integration of discrepant intensities in a single percept.

Across three experiments, we demonstrated that: (1) when the individual components of a multi-touch stimulus are discrepant, the perceived total intensity is overestimated; (2) the underlying mechanism appears to be an increased weighting of more salient stimuli in the cognitive process of aggregating the individual components; (3) this salience-based reweighting reflects a change in perceptual sensitivity, rather than a cognitive heuristic or response bias; (4) the reweighting process is not a trivial consequence of merging or ‘funnelling’ of the component stimuli, since it is present even

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3 when participants clearly perceive two distinct stimuli, and can report the intensity of
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5 either stimulus alone; (5) the reweighting process is pre-attentive and automatic, since
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7 overestimation can occur even when the discrepancy between individual component
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9 stimuli cannot be perceived; (6) the data can be explained by a simple model that uses
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11 divisive normalisation to compute the salience of component stimuli, and then weights
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13 the contribution of each component to the total percept by its salience.
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Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

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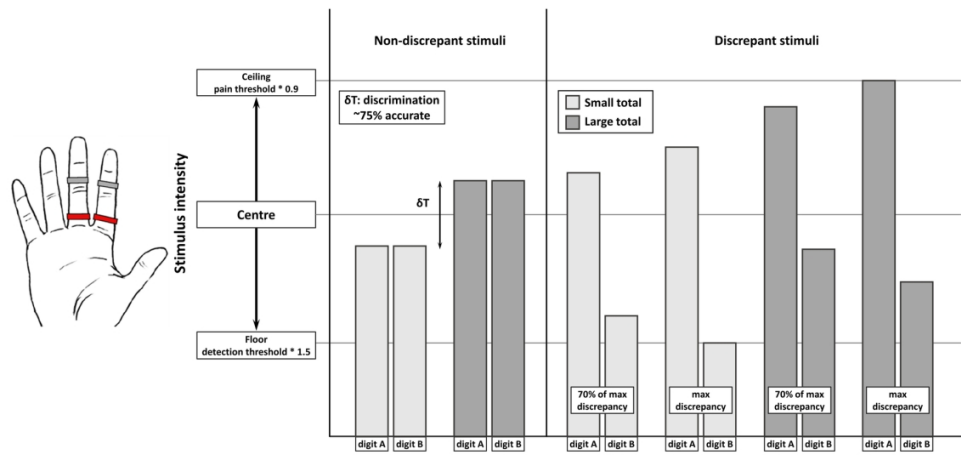


Figure 1. Stimulation levels for Experiment 1 (non-discrepant stimuli and 70% discrepant stimuli) and Experiment 2 (all the stimuli). In both experiments, electrodes were placed on participants' right index and middle fingers. The intensity of the electro-tactile stimulation in each condition was established on the basis of individual detection and pain thresholds. For non-discrepant stimulus pairs, intensities were chosen so that participants discriminated small from large stimuli at approximately 75% correct. In Experiment 1 stimulus pairs were based on 70% of this maximal discrepancy. In Experiment 2, aside the 70% discrepant stimuli, maximally discrepant stimuli spanned the range from detection to pain thresholds, and were total-matched to non-discrepant stimuli.

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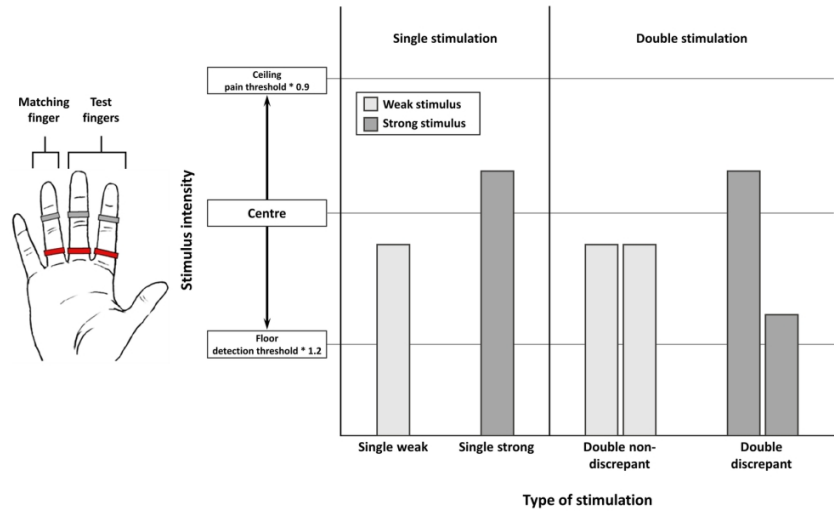


Figure 2. Stimulation of index and middle fingers in Experiment 3, was discrepant or non-discrepant as in Experiment 1. Additional trials delivered weak or strong stimuli either to index or middle fingers alone, matching the intensity of component stimuli in stimulus pairs. Participants adjusted shocks to ring finger to have the same perceived intensity of the stimuli delivered to index and middle fingers.

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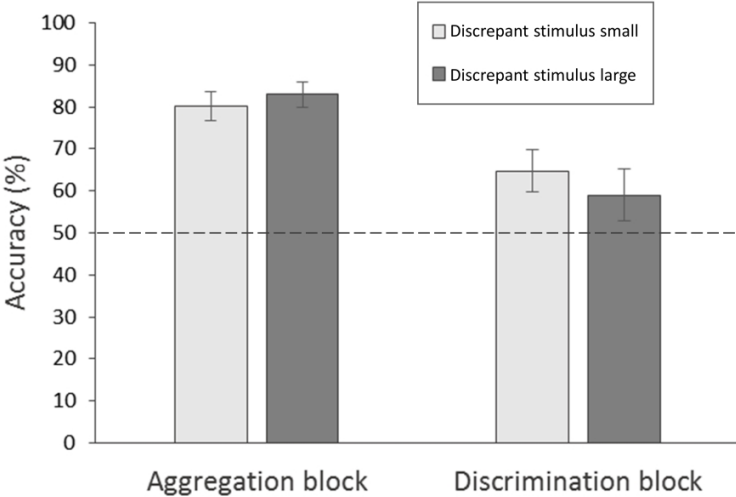


Figure 3. Accuracy in the Aggregation/Discrimination blocks in Experiment 1. Participants’ performance was significantly higher in the Aggregation block compared to the Discrimination block. Accurate judgement of total intensity was possible even if discrimination of the overall discrepancy between the stimuli was just slightly above chance level. The dashed line represents the chance level (50%). Error bars show standard error of the mean.

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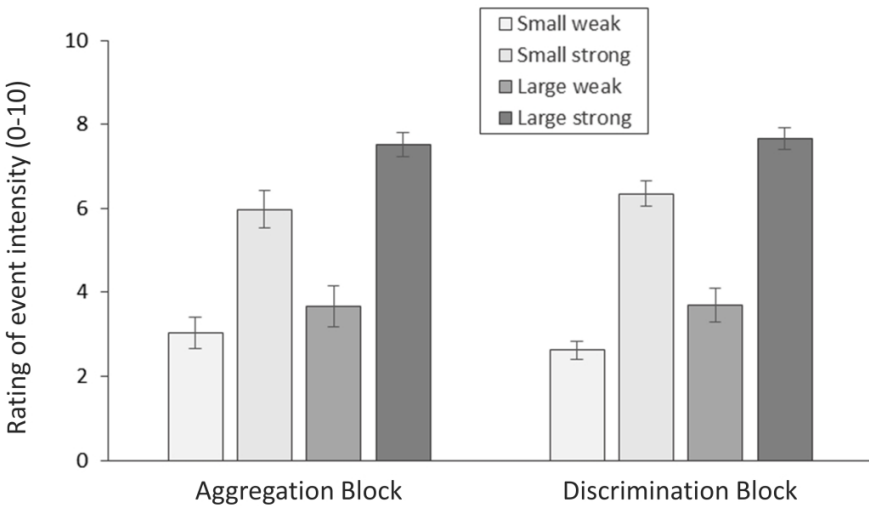


Figure 4. Magnitude estimate of single events in the rating trials presented in Experiment 1. Participants showed accurate perception of the intensity of each stimulus (weak/strong event, small/large total) in both the Aggregation and the Discrimination block. Error bars show standard error of the mean.

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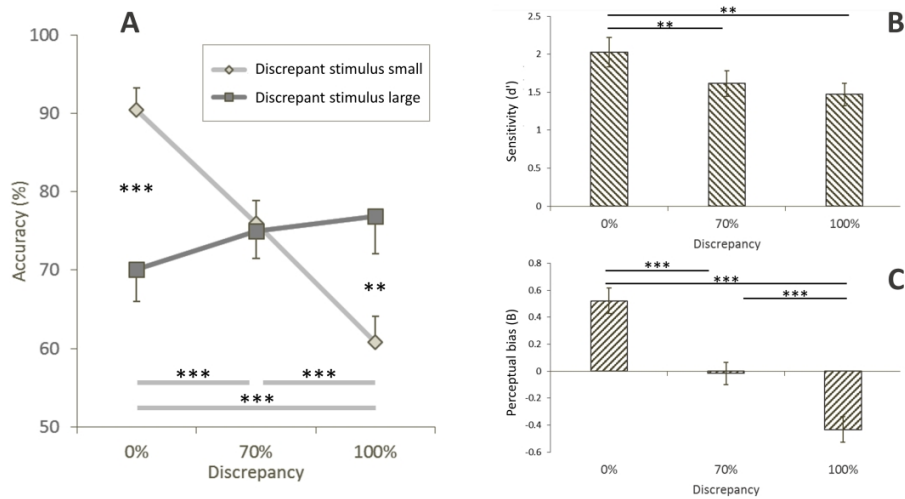


Figure 5. Accuracy, sensitivity, and perceptual bias along discrepancy in Experiment 2. Participants' accuracy (A) decreased along with discrepancy when the discrepant pair had a small total intensity, but not when the discrepant stimulus had a large total intensity. Both sensitivity (B) and perceptual bias (C) were significantly modulated by the discrepancy between the two simultaneous stimuli in the pair. Error bars show standard error of the mean.

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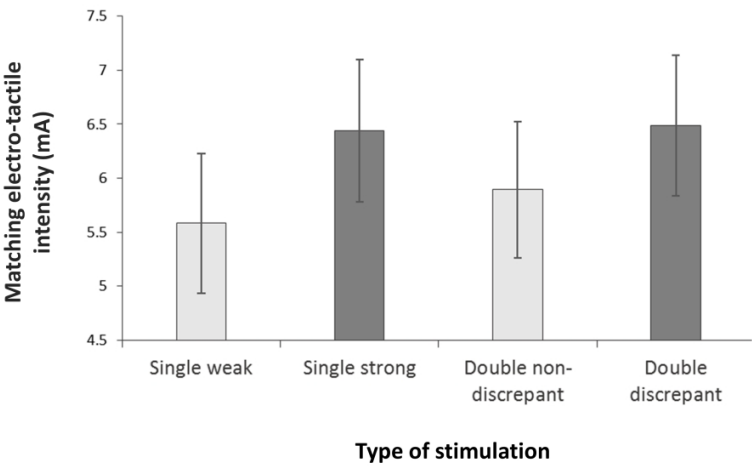


Figure 6. Matching electro-tactile intensity of single/double weak/strong stimuli in Experiment 3. Participants perceived a larger total intensity when a strong stimulus was present in the stimulation, compared to when the single or double stimulation was composed by the small stimulus/i, suggesting that the perception of double discrepant stimulation is strongly biased towards the more salient stimulus in the pair.

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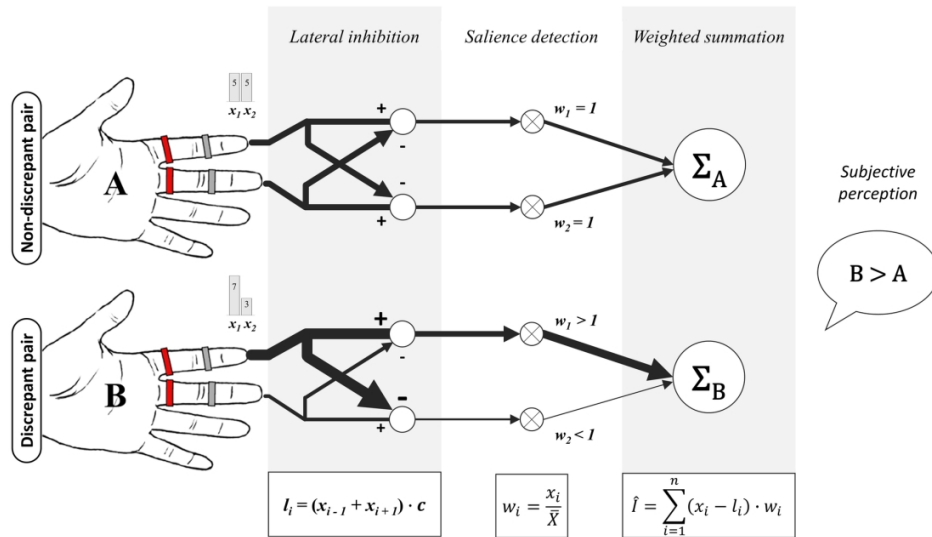


Figure 7. Putative model of somatosensory integration of multiple discrepant and non-discrepant stimuli. A. When non-discrepant multiple simultaneous somatosensory stimuli are aggregated in a total percept, the physical intensity delivered to each finger (i) is first reduced by lateral inhibition (l_i) (top left of the scheme). Experiment 1 shows that at this stage, the intensity of each input after lateral inhibition is retrievable. Next, in non-discrepant pairs, the salience value is the same for both stimuli. Therefore, the weight assigned to each stimulus (w_i) is 1 (top centre of the scheme), and the weighted summation of the events only reflects the sub-additive effect of lateral inhibition (top right of the scheme). B. Multiple discrepant stimuli are also subject to lateral inhibition from the adjacent fingers. However, the amount of lateral inhibition is different among the stimuli, with the weak stimuli producing less inhibition of the strong stimuli (bottom left of the scheme). Single stimulus intensity of discrepant patterns after lateral inhibition is also accessible. Next, as the strong stimulus is larger than the average intensity of the multiple stimulation, the weight assigned to it is > 1 , while the weight of the weak stimulus is < 1 (bottom centre of the scheme). Finally, the weighted summation of the discrepant pair is biased towards the strong stimulus in the pattern (bottom right of the scheme). As a result, the comparison between equally-intense non-discrepant and discrepant pairs produces an overestimation of the discrepant pattern, driven by the salience of the strongest stimulus (far right of the scheme).

169x95mm (300 x 300 DPI)

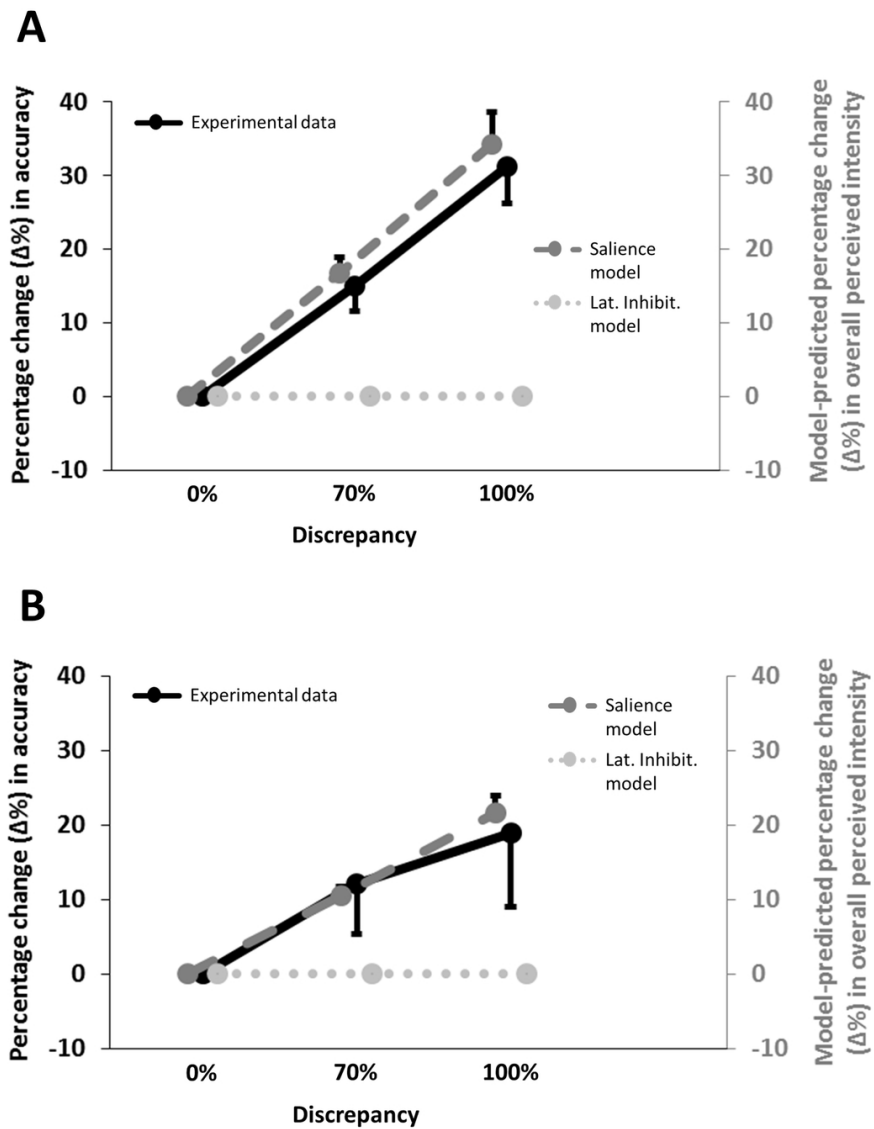


Figure 8. Actual and predicted percentage change between the non-discrepant condition (0%) and the two discrepant conditions in Experiment 2 (70%, 100%) for the small (A) and the large (B) totals. Experimental data (black line) are referred to the left Y axis, and perceived intensities predicted by the models (grey lines) are referred to the right Y axis. The lateral inhibition model (dotted grey line) predicts no change in perception of overall intensity as a function of discrepancy. Error bars show standard error of the mean.

94x117mm (300 x 300 DPI)

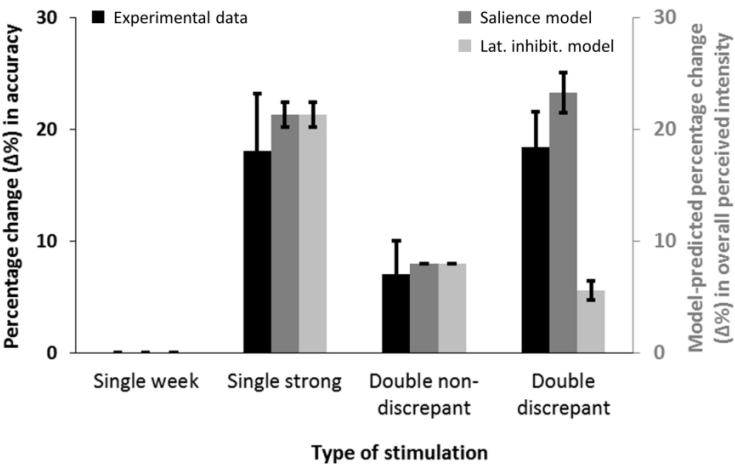


Figure 9. Actual and predicted percentage change between the single weak stimulus condition and the other conditions in Experiment 3 (single strong, double non-discrepant, double discrepant). Experimental data (black bar) are referred to the left Y axis, and predicted intensities (grey bars) are referred to the right Y axis. Both models predicted the same results for the double non-discrepant condition, where the two inputs had equal salience. However, the two models produced very different outcomes for the double discrepant condition, where one stimulus in the pair was more salient (was stronger than the average of the total stimulation). Note that model performance is consistent with the previous simulations of Experiment 2 (see Figure 8), where the lateral inhibition model predicted no change in perception of overall intensity at different levels of discrepancy. Here, the numerical difference between the non-discrepant and discrepant double stimulations for the lateral inhibition model is due to the fact that the intensity of x_1 and x_2 in Experiment 3 were adjusted to be perceptually, rather than physically identical. Error bars show standard error of the mean.

169x95mm (300 x 300 DPI)

<i>Model</i>	<i>No. Par</i>	<i>AIC</i>	<i>AICc</i>	<i>Δ(AICc)</i>	<i>w(AICc)</i>	<i>ER</i>
<i>Small total</i>						
Saliency model	1	355.06	355.13	0	> 0.999	1.66 x 10 ⁷
Lateral inhibition	1	388.31	388.38	33.24	< 0.001	
<i>Large total</i>						
Saliency model	1	417.73	417.80	0	0.85	5.84
Lateral inhibition	1	421.26	421.33	3.53	0.15	

<i>Model</i>	<i>No. Par</i>	<i>AIC</i>	<i>AICc</i>	<i>Δ(AICc)</i>	<i>w(AICc)</i>	<i>ER</i>
Saliency model	1	208.87	208.98	0	0.99	104.4
Lateral inhibition	1	218.17	218.27	9.30	0.01	