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Numerical Priming Between Touch and Vision Depends on Tactile Discrimination

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Abstract
Although the interaction between vision and touch is of crucial importance for perceptual and bodily self-consciousness, only little is known regarding the link between conscious access and tactile processing. Here, we tested whether the numerical encoding of tactile stimuli depends on conscious discrimination. On each trial, participants received between zero and three taps at low, medium, or high intensity and had to enumerate the number of visual items subsequently presented as a visual target. We measured tactovisual numerical priming, that is, the modulation of reaction times according to the numerical distance between the visual target and tactile prime values. While numerical priming and repetition priming were respectively elicited by high and medium intensity stimuli, no effect was found for low intensity stimuli that were not discriminable. This suggests that numerical priming between touch and vision depends on tactile discrimination. We discuss our results considering recent advances in unconscious visual numerical priming.

Keywords
visual perception, tactile perception, numerosity, priming

Introduction

While the quest for consciousness has made tremendous progress in the visual domain (Dehaene & Changeux, 2011; Koch, 2004), its extension to other sensory modalities

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remains limited. Yet, a multimodal study of consciousness seems necessary in order to fully understand the origins of phenomenal experience (Faivre, Salomon, & Blanke, 2015). In addition, the sense of touch is held to be of crucial importance for bodily self-consciousness, that is, the sense of owning one's body and perceiving the world from an embodied first-person perspective (Blanke, 2012). Despite the relevance of touch for consciousness studies, only little is known regarding the unconscious processing of tactile stimuli (see Gallace & Spence, 2008 for a review). This lack of knowledge prevents from delineating the neural and cognitive correlates of tactile awareness using the contrastive approach, which has proven to be fruitful in the visual domain (Baars, 1997).

Here, we sought to extend the description of conscious and unconscious tactile processing by focusing on numerosity signals, as nonsymbolic digits represent a straightforward stimulus in the tactile domain (e.g., number of simultaneous tactile taps delivered on the finger tips). We focused here on small numerosity values (i.e., up to three tactile taps), for which conscious tactile enumeration has already been described (Riggs et al., 2006). Recently, cross-modal effects between visual Arabic digits and nonsymbolic tactile taps were shown using a matching task, in which participants had to indicate whether the visual digit matched the amount of tactile taps they received (Krause, Bekkering, & Lindemann, 2013). Participants were found to be faster and more accurate as the distance between the tactile and visual digit became larger, a phenomenon known as the numerical distance effect (Moyer & Landauer, 1967). These results suggest not only the existence of a direct link between tactile sensations and numerosity but also a common encoding format between vision and touch. The current study aimed at testing whether tactile numerosity encoding and tactovisual transfer are enabled in case the tactile taps are not consciously felt. Our hypothesis is motivated by several lines of evidence. First, unconscious processing of numerosity in vision is well documented, as invisible prime stimuli conveying either symbolic or nonsymbolic numerosity signals are known to induce priming effects under various techniques such as masking (Dehaene, Naccache, Le Clec', Koechlin, & Mueller, 1998), continuous flash suppression (Bahrami et al., 2010), or crowding (Huckauf, Knops, Nuerk, & Willmes, 2008; see Dubois & Faivre, 2014 for a comparison of various techniques used to make stimuli invisible). Second, cross-modal unconscious effects pertaining to numerosity processing are now well established, notably between a subliminal (i.e., consciously unaccessible) visual prime digit and a supraliminal (i.e., consciously accessible) auditory target (Kouider & Dehaene, 2009), and even between two subliminal audiovisual stimuli conveying numerosity information (Faivre, Mudrik, Schwartz, & Koch, 2014). Yet, while low-level interactions between a supraliminal tactile stimulus and a subliminal visual one are documented (Lunghi, Binda, & Morrone, 2010), no study to our knowledge has investigated cross-modal influences from subliminal stimulus in the tactile domain.

To test the encoding of tactile numerosity signals without awareness, we developed a cross-modal (i.e., tactovisual) procedure of numerosity priming (Figure 1). Participants sat in front of a screen, their dominant hand resting palm up on a desk. They received one to three simultaneous tactile taps (the tactile prime) on their finger tips, which could be of low, medium, or high intensity (see Methods section). The low intensity taps were designed to remain under the threshold of conscious access, while the two other intensities elicited conscious percepts. The tactile prime was followed by a visual target composed of one to three items, which participants had to enumerate as fast and accurately as possible. Subsequently, they were asked to report the subjective percept associated with the tactile prime, by indicating whether they perceived no tactile stimulus, a vague tactile sensation, or a clear tactile sensation. This subjective measure of awareness was used to estimate tactile discrimination on a single-trial basis, and therefore exclude the few trials in which the

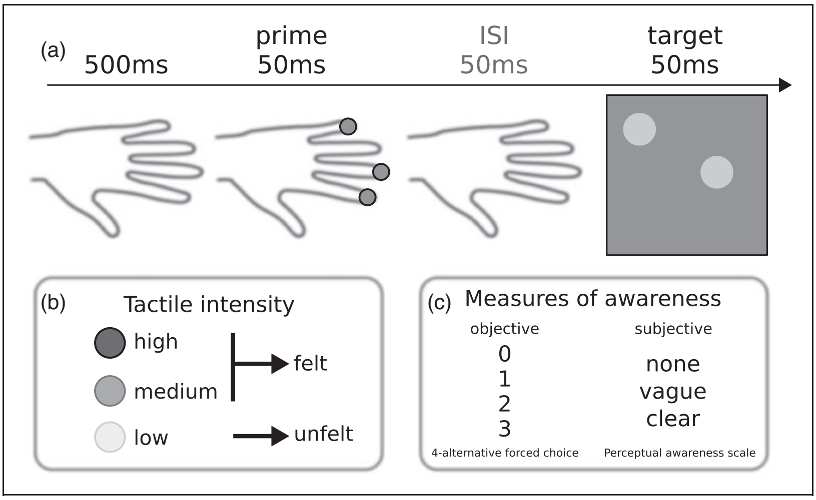

Figure 1. Experimental procedures. (a). On each trial, participants received between 0 and 3 tactile taps (three depicted here) on any finger but the thumb. Following an interstimulus interval, a visual target containing between 1 and 3 items (2 are depicted here) was displayed. Participants had to enumerate as fast as possible the number of visual items. (b). Tactile taps were delivered with high, medium, or low intensity, the latter condition being under the threshold for conscious access. (c). Tactile discriminability was controlled using subjective measures in the main tactovisual priming block, and with a combination of objective (four-alternative forced choice task on the number of tactile taps received) and subjective measures in a control block.

low-intensity taps were consciously accessed. Numerosity priming was defined by a modulation of reaction times as a function of the distance between the prime and target values. Based on previous results (Roggeman, Verguts, & Fias, 2007), we expected this modulation to take the form of a step-like function, in which priming occurs when the prime value is smaller than the target value, or a V-shaped function, in which priming decreases symmetrically as the numerical distance between the target and the prime value increases. Following this measure of numerosity priming, we ran an additional control session, in which participants were presented with the same sequence of stimuli but had to enumerate the tactile prime, and then provide a subjective report of the associated percept. This combination of subjective and objective measures was used to estimate how tactile discrimination in the low, medium, and high intensity conditions affected numerosity priming, and therefore assess the role of tactile awareness during tactile numerosity processing.

Methods

Participants

Twenty right-handed participants (seven females, mean age = 21.8 years, $SD = 3.0$ years) from the student population at Ecole Polytechnique Fédérale de Lausanne took part in this study, in exchange for a monetary compensation (30 CHF). All participants had normal or corrected-to-normal sight, and no psychiatric or neurological history. They were naive to the purpose of the study and gave informed consent, in accordance with institutional guidelines and the Declaration of Helsinki.

Stimuli

The prime stimuli consisted of one, two, or three simultaneous mechanical taps, randomly delivered on the finger tips (apart from the thumb) of the dominant hand by means of a MSTC3 tapper controller (M & E Solve, United Kingdom). Note that all prime values were within the subitization range (Kaufman & Lord, 1949). Primes could be of three possible intensities. The low intensity condition corresponded to the intensity level at which participants stopped feeling a tap delivered by the experimenter on the right index finger (mean intensity = 1.23 V, $SD = 0.08$). Intensities in the medium and high intensity conditions corresponded respectively to 1.5 and 2.25 times the low intensity condition. The combination of stimulated fingers was counterbalanced across prime value, and not further investigated (see Krause et al., 2013 for tactile processing of numerosity and counting habits). A custom made hand rest was used to avoid variations in finger spacing across participants and experimental sessions. The target stimulus consisted of a 5° by 5° dark gray square containing one to three light gray disks (0.21 Michelson contrast). The sizes of the disk were randomized to minimize confounding size and total surface area (Bahrami et al., 2010). The disks' diameters were sampled from uniform distributions with overlapping tails, so that the size of an individual disk was not informative regarding the number of items (numerosity = 3: mean diameter = 0.9° (range: 0.8–1.1); numerosity = 2: mean diameter = 1.1° (range: 0.9–1.3); numerosity = 1, mean diameter = 1.55° (range: 1.2–1.9)). Within one trial, all disks had the same size. Stimuli were presented using ExpyVR, a custom-built multimedia presentation software developed with Python 2.6 and the Open Graphics Library v.2.2 (freely available from http://lnco.epfl.ch/expyvr) on a 1024 × 768 pixels laptop screen.

Procedure

After filling in a questionnaire for demographic data, participants were fitted with four solenoid tappers, as well as noise-canceling headphones. They were sitting at a desk in front of a screen, with their hands in front of them, fingers straight, and palms facing up. In the main session (tactovisual priming), participants received between one and three simultaneous tactile taps (the prime) lasting 50 ms; 23.1% of total trials served as baseline, in which no tactile stimulation was delivered. After an interstimulus interval of 100 ms, the tactile prime was followed by the visual target stimulus presented for 50 ms. Participants were asked to enumerate as fast and accurately as possible the disks contained in the visual target, by means of a key press with their nondominant hand. Subsequently, they reported whether they perceived no tactile stimulus, a vague tactile sensation (i.e., not confident about the number of taps), or a clear tactile sensation (i.e., confident about the number of taps). This block contained 162 baseline trials and 540 test trials, with 108 trials for each numerical distance between the target and the prime (i.e., including 198 trials with a prime value of 1, 144 trials with a prime value of 2, and 198 with a prime value of 3). An equal number of trials was attributed to each intensity condition. In a subsequent control block, participants were presented with the same sequence of stimuli, and were asked to enumerate the number of tactile taps they felt, and rate their subjective sensation using the same scale as previously described. This block contained 234 trials including 54 baseline trials, with 36 trials per numerical distance (i.e., including 66 trials with a prime value of 1, 48 trials with a prime value of 2, and 66 with a prime value of 3). An equal number of trials was attributed to each intensity condition. Trial order was fully randomized. The total duration of the experiment was about 90 minutes.

Statistical Analysis

Reaction times below 200 ms, or beyond two standard deviations from the mean were discarded (corresponding to 3.9% of total trials), as well as trials in which participants reported a clear tap in the low intensity condition (1.3% of total trials), or trials in which the target was categorized erroneously (i.e., response errors, corresponding to 5.7% of total trials). To quantitatively describe the shape of priming curves as a function of the numerical distance between target and prime values, we conducted linear regressions similar to those reported by Roggeman et al. (2007). This analysis did not include baseline trials in which no prime was presented and was run for each participant separately. We fitted regression equations with two predictors that coded for a step-like function and a V-shaped function. The step-function predictor had a coefficient of -1 if the prime value was superior or equal to the target value and a coefficient of $+1$ if the prime value was inferior to the target value. The V-shaped function predictor had coefficients equal to the absolute value of the difference between the target and prime values. Null effects were assessed using JZS Bayes factor tests with default prior scales (Rouder, Morey, Speckman, & Province, 2012) so that a Bayes factor (B) <0.33 implies substantial evidence for the null hypothesis, $0.33 < B < 3$ suggests insensitivity of the data, and $B > 3$ implies substantial evidence for the alternative hypothesis. All analyses were performed with R (R Core Team, 2013) including the BayesFactor package (Morey & Rouder, 2015).

Results

To estimate numerosity priming, we conducted a repeated measures analysis of variance (ANOVA) on reaction times with prime intensity, prime value, and target value as within-subject factors. This analysis revealed a three-way interaction ($F(8, 152) = 2.50$, $p = .01$, partial $\eta^2 = 0.12$) that we further explored by running separate ANOVAs in each intensity condition. In the low intensity condition, no effect reached significance (main effect of prime value: $F(2, 38) = 0.51$; main effect of target value: $F(2, 38) = 1.54$; interaction: $F(4, 76) = 2.07$). By contrast, an interaction between prime value and target value was found both in the medium intensity ($F(4, 76) = 3.27$, $p = .016$, partial $\eta^2 = 0.15$) and high intensity ($F(4, 76) = 2.54$, $p = .04$, partial $\eta^2 = 0.12$) conditions. These results suggest that prime values had an influence on reaction times when presented at medium and high intensities, but not at low intensity. This effect was further corroborated by an ANOVA with prime intensity and numerical distance as within-subject factors, which showed an interaction between the two terms ($F(8, 152) = 2.66$, $p = .01$, $\eta^2 = 0.12$). We next plotted reaction times as a function of the distance between target and prime values (Figure 2). Even though we found no systematic difference in reaction times depending on the target value in baseline trials ($F(2, 38) = 1.90$, $p = .16$), no baseline correction was performed to avoid spurious contaminations (see Discussion section). Instead, following previous studies (Hesselmann, Darcy, Sterzer, & Knops, 2015; Roggeman et al., 2007), we established the difference in the priming-curve shapes, by regressing the raw reaction times with two predictors that coded for a step-like function and a V-shaped function (see Methods section). In the medium intensity condition, we found that the priming curve was better described by the V-shaped function ($t(19) = 2.12$, $p = .048$) than by the step-like function ($t(19) = -1.36$, $p = .19$; difference between the two models: $t(19) = 2.11$, $p = .048$). In addition, an ANOVA with distance as within subject factor but without distance 0 (i.e., getting rid of the trials in which the prime value was equal to the target value) failed to reach significance ($F(3, 57) = 0.25$, $p = .86$, partial $\eta^2 = 0.01$). This negative finding was confirmed using a Bayesian ANOVA, which showed that without

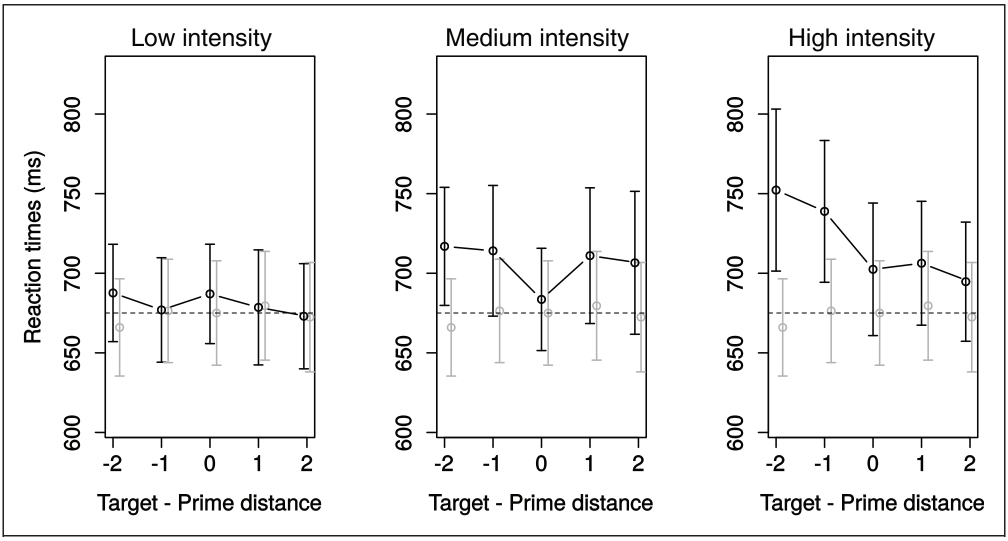

Figure 2. Priming results. Reaction times according to [target—prime] numerical distance are represented in black for prime present trials and in gray for baseline trials, in the low (left panel), medium (middle panel), and high intensity condition (right panel). The baseline was calculated considering the trials with no tactile prime in which the target value corresponded to the specific numerical distance between the target and the prime. The dashed line represents the average reaction time across numerical distances. Error bars represent the standard error of the mean.

distance 0, the null model was preferred over the model with numerical distance by a factor of about 11 (i.e., Bayes Factor = 0.09, see Rouder et al., 2012, and Methods section). Altogether, these results suggest that the V-shaped function in the medium intensity condition mostly stemmed from a repetition priming effect. In the high intensity condition, we found the data to be better fitted by the step-like function ($t(19) = -3.51$, $p = .002$) than by the V-shaped function ($t(19) = 1.70$, $p = .11$; difference between the two models: ($t(19) = 2.90$, $p = .009$). This result is consistent with previous findings showing step-like priming function from nonsymbolic visual primes (as opposed to the V-function, typically resulting from symbolic visual primes, see Roggeman et al., 2007). As opposed to the medium intensity condition, here priming held even when excluding trials with distance 0 ($F(3, 57) = 7.17$, $p < .001$, partial $\eta^2 = 0.27$). These results are similar to what is known from visual studies, in which participants were found to be slower in trials in which the [target—prime] distance was negative and faster when this distance was positive, as compared with a baseline condition in which no prime was presented (Bahrami et al., 2010). While in these studies reaction times for positive distances were shorter than baseline trials, they remained longer in our case, for a reason that will require further exploration. Altogether, our results suggest no numerosity priming at low intensity, repetition priming at medium intensity, and numerical priming at high intensity.

In a following control block, we then assessed how participants could discriminate tactile primes using both a subjective measure (perceptual awareness scale) and an objective measure (four-alternative forced choice task between prime values from 0 to 3). At the subjective level, an ANOVA with the value and intensity of tactile taps as within subject factors showed a main effect of intensity ($F(2, 38) = 465$, $p < .001$, partial $\eta^2 = 0.99$), reflecting higher subjective ratings for medium and high intensities than for low intensity (Figure 3(a)). It also showed a

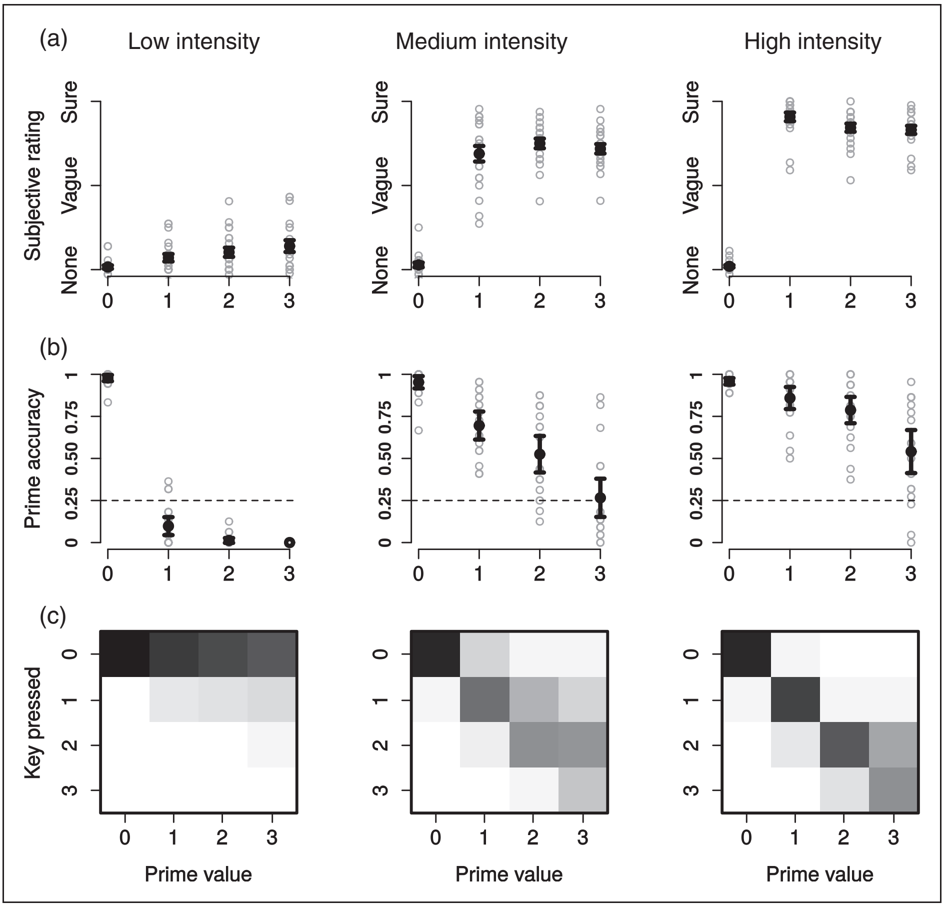

Figure 3. Subjective and objective measures of awareness in the low (left column), medium (middle column), and high intensity conditions (right column) (a). Subjective reports (no, unclear, or clear tactile percept) depending on the prime value. (b). Accuracy scores on the four-alternative forced choice task depending on the prime value. In (a) and (b), gray dots represent individual data and black dots the corresponding average. Error bars represent the standard error of the mean. (c). Confusion matrices between the prime value and the response provided during the four-alternative forced choice task. Response percentages are coded with a linear gray scale, with black and white corresponding respectively to 100% and 0% of responses provided.

main effect of numerical value ($F(3, 57) = 367$, $p < .001$, partial $\eta^2 = 0.95$), reflecting that participants could easily discriminate the absence of tactile stimulus (they reported "no perception" in 94.2% of baseline trials), but reported vague perception mostly for values >1, suggesting that higher values were more difficult to discriminate (Figure 3(a)). In addition, an interaction between numerical value and intensity ($F(6, 114) = 118$, $p < .001$, partial $\eta^2 = 0.86$) reflected that subjective ratings linearly increased with numerical value in the low intensity condition, while it plateaued in the medium and high intensity conditions for numerical values >1. The results obtained with the objective measure closely matched those from the subjective one: A one-way ANOVA with participants as the random variable revealed a main effect of numerical value ($F(3, 57) = 156.0$, $p < .001$, partial $\eta^2 = 0.89$), reflecting that accuracy was lower for high numerical values (see Figure 3(b)), a main effect of intensity ($F(2, 38) = 167.2$, $p < .001$, partial $\eta^2 = 0.99$), reflecting that accuracy increased with intensity, and finally an interaction between numerical value and intensity ($F(6, 114) = 47.45$, $p < .001$, partial $\eta^2 = 0.71$), revealing that accuracy decreased more for high numerical values at low intensity. In the low intensity condition, accuracy was below chance-level performance (i.e., $<25\%$) for all values in trials in which a tap was delivered (all $p < .001$), suggesting that participants did not detect the taps in most cases, and therefore responded that none was presented. In addition, participants could discriminate that three taps were delivered at high intensity better than chance-level performance (54.1%, $t(19) = 4.46$, $p < .001$), but not at medium intensity (27.4%, $t(19) = 0.27$, $p = .79$, bayes factor = 0.24). Likewise, corresponding subjective ratings were higher in the high versus medium intensity condition (paired t test: $t(19) = 5.88$, $p < .001$). Visual inspection of the confusion matrices between provided responses and actual numerical values suggests that taps remained undetected in most trials in the low intensity condition, while errors mostly stemmed from confusion between numerical values of two and three in the medium- and high- intensity conditions (Figure 3(c)). Despite the important intersubject variability in tactile discrimination at the subjective and objective level, no correlation was found with the amplitude of priming.

Discussion

Using a tactovisual numerosity priming paradigm, we found evidence for the tactile encoding of numerosity only when the tactile prime stimuli were fully discriminable (i.e., high intensity condition). The data revealed that reaction times varied according to the numerical distance between the target and prime values following a step-like function, which is typical for nonsymbolic numerosity signals (i.e., noncanonical dot patterns, Roggeman et al., 2007). We therefore argue that discriminable tactile stimuli can be subitized, an issue that has been debated. Indeed, using enumeration tasks instead of priming, it was found that accuracy and naming times varied with numerosity, with close to perfect accuracy for numbers between one and three, and a severe impairment in the range of four to six (Riggs et al., 2006). Yet, this effect was not observed when the stimulation was delivered on the full body (Gallace, Tan, & Spence, 2006), and it was later suggested that it was likely to reflect a bias in the interpretation of psychometric functions rather than numerosity processing (Gallace, Tan, & Spence, 2008). Thus, by relying on tactovisual numerosity priming instead of direct enumeration tasks, our results bring new evidence in favor of tactile numerosity encoding, and suggest in line with recent results that tactile and visual numbers are encoded with a similar format within the range of subitization (Krause et al., 2013). It will be interesting to estimate the limits of tactile numerosity encoding, and test if tactile counting is also enabled for numerical values greater than four, and if tactile subitizing and tactile counting involve distinct or similar mechanisms (for visual numerosity, see Burr & Ross, 2008; Piazza, Mechelli, Butterworth, & Price, 2002). In addition, future studies should control that the step-like function is not due the summed intensity of stimulation, but rather by the actual number of taps delivered (e.g., by normalizing the taps intensities by their number).

When intensity was slightly decreased (i.e., medium intensity condition), we found a priming effect only when prime and target stimuli shared the same numerosity. This repetition priming effect is likely to reflect lower-level forms of representation in the presence of weaker tactile signals. Finally, in case the tactile prime was not detected consciously (i.e., low intensity condition), no priming effect was found. We therefore conclude that numerical priming between touch and vision depends on conscious tactile discrimination. The results we obtained in the unconscious condition are reminiscent of a recent study that cast doubts on the existence of unconscious processing of nonsymbolic visual numerosity signals (Bahrami et al., 2010). Indeed, while Bahrami et al. reported that baseline-corrected reaction times varied linearly according to the numerical distance between target and prime values, Hesselmann and Knops (2014) argued that this linear priming function stemmed from a spurious baseline correction, due to the fact that reaction times were modulated not only by the target value but also depending on the presence versus absence of the prime (i.e., interaction between the target value and absence vs. presence of the prime). Accordingly, in a follow-up study focusing on raw reaction times (Hesselmann et al., 2015), it was found that invisible prime stimuli induced repetition priming (signed by a V-shaped priming curve) but not numerical priming, akin to what we found in the medium intensity condition. Note that both in Bahrami and Hesselmann studies, the visual prime served as an "alerting cue" to enumerate the subsequent visual target, since reaction times were overall longer in baseline trials where no prime was presented. By contrast, tactile primes in our study slowed down reaction times to enumerate the visual target, suggesting that prime stimuli have opposite effect on alertness in unimodal versus cross-modal conditions. Such cross-modal distraction decreased with tactile intensity (compare baseline vs. priming curves across intensity conditions in Figure 2), which suggests that tactile awareness may also play a role at this level.

It will be interesting to assess whether the absence of unconscious priming in our study stems from tactile processing, or tactovisual transfer. To test the first hypothesis, one could investigate lower level forms of unconscious tactile processing, for instance, involving a single subliminal tap as an attentional cue. As for the second hypothesis, one may restore tactovisual transfer by using a common reference frame between touch and vision, as bodily signals including touch and proprioception are known to impact vision (for a review, see Faivre, Salomon, & Blanke, 2015). Notably, proprioceptive (Salomon, Lim, Herbelin, Hesselmann, & Blanke, 2013) and tactile signals (Lunghi et al., 2010) are known to influence conscious access during binocular suppression. In addition, spatial distance between tactile and visual cues is known to disrupt illusions of body ownership (Lloyd, 2007). Thus, tactovisual transfer may be more potent in case participants constantly stare at their hand (hereby inducing visual enhancement of touch, see Kennett, Taylor-Clarke, & Haggard, 2001), the visual targets being subsequently presented on the same fingers receiving the tactile taps. A finer estimation of the scope of unconscious tactile processing can be obtained only by pursuing such experiments, which in our opinion is needed to fully understand perceptual awareness beyond vision.

Conflict of interest

None declared.

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