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Cross-modal cueing effects of visuospatial attention on conscious somatosensory perception

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Abstract

Objective: The impact of visuospatial attention on perception with supraliminal stimuli and stimuli at the threshold of conscious perception has been previously investigated. In this study, we assess the cross-modal effects of visuospatial attention on conscious perception for near-threshold somatosensory stimuli applied to the face.

Methods: Fifteen healthy participants completed two sessions of a near-threshold cross-modality cue-target discrimination/conscious detection paradigm. Each trial

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began with an endogenous visuospatial cue that predicted the location of a weak near-threshold electrical pulse delivered to the right or left cheek with high probability ($\sim$75%). Participants then completed two tasks: first, a forced-choice *somatosensory discrimination task* (felt once or twice?) and then, a *somatosensory conscious detection task* (did you feel the stimulus and, if yes, where (left/right)?). Somatosensory discrimination was evaluated with the response reaction times of correctly detected targets, whereas the somatosensory conscious detection was quantified using perceptual sensitivity (d′) and response bias (beta). A 2×2 repeated measures ANOVA was used for statistical analysis.

Results: In the somatosensory discrimination task (1st task), participants were significantly faster in responding to correctly detected targets ($p < 0.001$). In the somatosensory conscious detection task (2nd task), a significant effect of visuospatial attention on response bias ($p = 0.008$) was observed, suggesting that participants had a less strict criterion for stimuli preceded by spatially valid than invalid visuospatial cues.

Conclusions: We showed that spatial attention has the potential to modulate the discrimination and the conscious detection of near-threshold somatosensory stimuli as measured, respectively, by a reduction of reaction times and a shift in response bias toward less conservative responses when the cue predicted stimulus location. A shift in response bias indicates possible effects of spatial attention on internal decision processes. The lack of significant results in perceptual sensitivity (d′) could be due to weaker effects of endogenous attention on perception.

Keywords: Neuroscience, Neurology, Physiology, Medical imaging

1. Introduction

Spatial attention is an adaptive mechanism that helps us interact with a complex multisensory world, and pursue specific goals while still being able to react to unexpected behaviorally significant events. The effects of spatial attention on conscious perception can be modulated by exogenous (bottom-up, involuntary, reflexive or stimulus-driven) and endogenous (top-down, voluntary or instruction/feature driven) orienting mechanisms. Recent evidence from behavioral and neuroimaging studies suggest that the former are two distinct attentional systems, subtended by partially overlapping brain circuits, including bilaterally distributed dorsal and ventral fronto-parietal networks, which can interact with each other in order to elicit optimal behavioral outcomes (Chica et al., 2013; Corbetta and Shulman, 2002; Corbetta et al., 2008).

Cue-target paradigms, comparing the perceptual impact of valid (i.e. signaling target location) vs. invalid (i.e. signaling a location different from target location) spatial

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cues, have been extensively used to study the effects of spatial attention on perception since made popular by Posner and collaborators in the eighties (Posner, 1994; Posner et al., 1980). In such, endogenous and exogenous attention modalities can be specifically evaluated by means of central or peripheral visuospatial cues that can be set up to be informative (or predictive, i.e., to signal the location of a subsequent target with a probability higher than chance levels (normally 75–80%), *endogenous attention*) or non-informative (non-predictive, i.e., to signal target location at chance levels, = or <50% target location, *exogenous attention*) about target location. Even if predictive spatial cues mainly engage endogenous attentional processes, they also carry exogenous contributions by virtue of a ‘pop-out’ or ‘phasic alerting’ tied to the onset of the cue itself, which cannot be ruled out completely.

While most spatial cueing experiments focused on the visual modality and used mainly supraliminal stimuli (i.e. stimuli well above the conscious perception threshold) (Egeth and Yantis, 1997), modulation of other sensory modalities (e.g. auditory, tactile) have also been addressed to understand the relationship between spatial attention and conscious perception. An effect that has been consistently reported is a decrease of reaction times and/or accuracy increases in response to stimuli presented in body sites or in spatial locations to which attentional resources are being allocated by attentional cues as those described above [see examples for visual (Carrasco and McElree, 2001); auditory (Spence and Driver, 1998); and somatosensory (Butter et al., 1989; Spence and McGlone, 2001; Yates and Nicholls, 2009) perception]. Moreover, spatial attention has been shown to improve different aspects of perception with regards to supraliminal stimuli, such as contrast sensitivity or spatial resolution (Carrasco et al., 2000; Yeshurun and Carrasco, 1998). Effects of attention on the detection of somatosensory stimuli have been associated to modulatory activity in contralateral somatosensory areas and bilaterally distributed temporo-parietal cortical sites associated with secondary somatosensory regions (Johansen-Berg et al., 2000; Mima et al., 1998; Puckett et al., 2017).

In addition to the above mentioned unimodal task designs (in which the cue and the target share the same sensory modality), cross-modal cueing paradigms (for example, visual cues modulating the perception of tactile stimuli) have been used to better pinpoint the impact of attention on somatosensory perception. To this regard, several authors have demonstrated improved perception of somatosensory stimuli with informative visual cues (Butter et al., 1989; Lloyd et al., 1999). For example, Butter et al. (1989) showed improved reaction times to tactile stimuli when they were preceded by either tactile or visual lateralized cues informing on stimulus location. Similarly, visual or tactile predictive peripheral cues improved detection of vibrotactile stimuli by orienting attention to stimuli (Chica et al., 2007).

While the aforementioned unimodal and cross-modal studies have focused on mainly supraliminal stimuli (i.e. visual or somatosensory stimuli presented well

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above the individual conscious perceptual threshold), the interest on how attention modulates near-threshold stimuli (i.e. weak stimuli detected only ∼50−60% of the times) has gained momentum in recent years. The relationship between spatial attention and conscious perception for near-threshold targets has been specifically explored within the visual modality (Chica and Bartolomeo, 2012; Chica et al., 2013; Chica et al., 2011; Smith, 1998). Using two common outcome measures of signal detection theory (Macmillan and Creelman, 2004), these studies have reported that spatial attention manipulated with visuospatial cues can modulate conscious access and induce improvements in perceptual sensitivity (d′) (i.e., the ability to detect trials accurately by either increasing the number of "hits", and/or also lowering the number "false alarms") and/or can shift the so-called response bias or response criterion (beta), a parameter gauging the likelihood of signaling the presence of a stimuli in the case of doubt. For example, Chica and colleagues (2011) showed that when near-threshold visual stimuli were preceded by valid peripheral visuospatial cues predictive about target location (exogenous plus endogenous components), spatial attention improved conscious perception as measured by an increase in perceptual sensitivity (d′) (more accurate detection) and shifted response bias (beta) towards less conservative (or more liberal) decision-making.

Extending these findings to the use of tactile stimuli in a cross-modal paradigm, Soto-Faraco et al. (2005) demonstrated improved perceptual sensitivity (more accurate detection) and faster reaction times for near-threshold tactile stimuli when preceded by central non-predictive social cues (Soto-Faraco et al., 2005). Similarly, spatially predictive looming visual stimuli approaching the face have been shown to induce enhancement of tactile perceptual sensitivity (d′) (Clery et al., 2015). Yet evidence on the effects of spatial attention on conscious perception of near-threshold somatosensory stimuli using peripheral predictive cues remains scarce and deserves further attention.

Adapting a well-tested behavioral paradigm manipulating visuospatial attention to the tactile modality (Chanes et al., 2012; Chica et al., 2011), we hereby assessed whether two aspects of lateralized somatosensory facial perception, tactile discrimination and conscious perception performed on the same near-threshold somatosensory stimuli can be modulated by spatial attention elicited by predictive peripheral cues. Cueing effects contrasting the impact of valid and invalid cues on somatosensory discrimination were tested using a forced-choice response quantified by means of the reaction time of correct responses. Signal Detection Theory outcome measures, perceptual sensitivity (d′) and response bias (beta), were employed to evaluate cue-driven modulation of conscious somatosensory detection. We hypothesized that orienting spatial attention to stimulus location would result in faster reaction times, improved perceptual sensitivity (d′) and a shift in response bias (beta) toward less conservative desicion making processes.

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2. Material and methods

2.1. Participants

Participants were recruited at the Neuromodulation Center, Spaulding Rehabilitation Hospital (Boston, MA, United States). The protocol was reviewed and approved by the Spaulding Rehabilitation Hospital institutional review board. All participants provided written informed consent to participate in the study. Participants of this study were recruited as part of a healthy control group in a larger clinical study. Therefore, exclusion criteria were determined to allow appropriate inclusion of the clinical population that was subsequently recruited. Fifteen healthy participants (7 women and 8 men) aged between 19 and 37 years old (mean $\pm$ SD: 25 $\pm$ 6 years old), with normal or corrected-to-normal vision, took part in this study. Exclusion criteria included: (1) a self-reported history of alcohol or substance abuse within the past 6 months, (2) diagnosis of any neurological disease (such as epilepsy), (3) episodes of seizures within the past 6 months, (4) unexplained loss of consciousness, (5) implanted medical devices or medical implants, and (6) being pregnant at the time of enrollment. Following the cross-over design of the above-mentioned larger clinical trial in which this study was embedded, healthy participants in our cohort, who were naïve as to the purpose of the experiment, carried out two baseline testing sessions (1st session and 2nd session) separated by at least 72 hours. Both testing sessions were identical in terms of the content of the task performed and the procedures followed.

2.2. Sample size calculation

Effect sizes from a prior study with a similar design and pursuing similar goals (Chica et al., 2011) were used to validate the size of our sample. Based on the effect sizes calculated from a study by Chica et al. (2011) (see experiment-4 of the study), we found that 8 participants would be required to detect a significant cueing effect in the somatosensory discrimination task for the reaction times of correct responses ($n = 13$, $F(1, 12) = 16.6$, effect size Cohen's d: 1.663). For the conscious somatosensory detection task, 12 subjects would be required to state significant differences in d' ($n = 13$, $F(1, 12) = 8.87$, effect size Cohen's d: 1.216). Finally, we estimated that 10 subjects would be required for significant changes in response bias (beta) ($n = 13$, $F(1, 12) = 10.64$, effect size Cohen's d: 1.33). Therefore fifteen subjects recruited for this trial appeared to be sufficient.

2.3. Apparatus and stimuli

During each session, participants performed the procedure described below. Visual stimuli were displayed on a screen using a PC computer (Dell, United States) and

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standard stimulus presentation software (E-prime, Psychology Software Tools, United States).

Participants were comfortably seated 57 cm away from the screen (distance at which 1 cm on the screen equals 1°). The experiment consisted in a cue-target paradigm including a total of 504 trials divided into 4 blocks. The somatosensory target consisted in either one or two (170 ms apart) near-threshold electrical pulses (type: monophasic; shape: quadratic, pulse width or duration: 200 μs) applied to the right or left cheek (zygomatic bone face area) by means of two surface disposable adhesive electrodes attached by 2 isolated electrical wires to a constant current stimulator (Digitimer DS7A, Digitimer Ltd, United Kingdom). The delivery location of somatosensory stimuli in the right or left cheek was adapted from a well-established paradigm used to assess visual influences on tactile perception (Tipper et al., 2001). Although other body parts, typically the hand or fingers, could have been more convenient to assess fine somatosensory perception (Chica et al., 2007), facial stimulation leaves the hands free allowing reliable manual responses.

The intensity of the current was determined by a titration procedure completed before the experiment. This allowed us to determine individually the somatosensory stimulus intensity at which ∼62% of the delivered somatosensory targets were consciously reported correctly (Chanes et al., 2012). The total number of trials needed to determine the 62% detection threshold during the titration block performed prior to the experiment varied across participants and ranged from 31 to 496 (172.6 ± 99.6, Mean ± SD). The mean value (for all subjects and blocks) for the intensity of the electrical pulses used for somatosensory stimulation was 2.8 mA ± 0.9 mA. The titration levels were verified and eventually further adjusted after each block of to account for practice and/or fatigue effects during the task.

Participants started the titration block receiving high-intensity somatosensory stimuli in their left or right cheek, which were progressively adjusted in steps of 0.05 mA in order to converge to the above-mentioned and previously established conscious detectability threshold (∼62%). This detection threshold level (same as used in (Chanes et al., 2012) for visual targets) was chosen to avoid floor or ceiling effects, allowing bidirectional modulations (improvement and worsening) of somatosensory target perception when combined with valid and invalid visuospatial cues. The experimental blocks only started once the intensity of the somatosensory stimulus providing that level of performance was reached.

2.4. Procedure

Each experimental trial consisted of the following events: (1) First, a period of fixation on a central cross presented on a computer screen; (2) the presentation of a peripheral visuospatial attentional cue on this same computer screen (either valid/

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invalid with regards to target location); (3) the delivery of a somatosensory target stimulus (absent or present, if present 1 or 2 brief electrical pulses) to the right or left cheek of the participant. Following that somatosensory target, participants were requested to complete on a computer keyboard two sequential tasks: First, (4) a *somatosensory discrimination task* (1st task) in which participants were asked to give a forced-choice response reporting whether 1 or 2 somatosensory pulses had been delivered to the face; once a response was provided, participants completed (5) a *somatosensory conscious detection task* (2nd task) indicating if they felt the stimulus on their cheek (yes/no) and if 'yes', to where they felt it (left/right cheek).

In further detail, each trial started with a screen with a gray background and a fixation cross ($0.5 \times 0.5°$) displayed at its center, which randomly lasted between 750 and 1250 ms (Fig. 1). Participants were asked to fixate on the central cross as soon as it appeared on the screen, signaling the start of the trial. Varying fixation intervals, as those implemented, are commonly used in attentional and perceptual paradigms to avoid the effects of fixed attentional expectancy to the subsequent appearance of the cue. Once the fixation cross disappeared, a peripheral visuospatial cue (consisting in a black dot of 2.2° diameter) was displayed on the computer screen for 67 ms at 12° of eccentricity to the left or the right side of the fixation cross. After the offset of the cue, the fixation cross was displayed again for an inter-stimulus interval (233 ms), prior to somatosensory target onset. This cue-to-target onset interstimulus interval was implemented to provide enough time for participants to process and integrate the information provided by the predictive visuospatial cues on potential somatosensory target location and orient attention accordingly. In all these processes, the varying fixation intervals (750−1250 ms), the cue duration (67 ms) and cue-to-target interval (233 ms) were based on multiples of the monitor refresh rate (60 Hz) and had been previously tested and validated in several studies in the visual domain (Chanes et al., 2012, 2013).

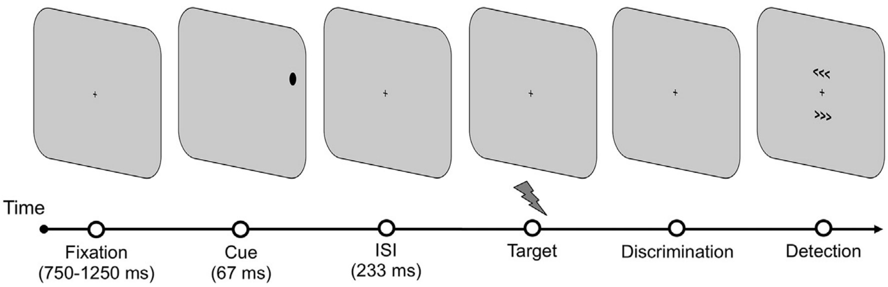

Fig. 1. Sequence of events in one single trial. Following a variable central fixation screen between 750 and 1250 ms, a peripheral visuospatial cue (75% validity) was presented for 67 ms. After an interstimulus interval of 233 ms, a somatosensory target (consisting in either 1 or 2 near-threshold electrical pulses) was delivered to participants' left or right cheek. Participants were asked to sequentially perform two tasks: first (1st task), a forced-choice *somatosensory discrimination task* (Was the stimulus delivered once or twice?) and, second (2nd task), a *somatosensory conscious detection task* [Did you feel the stimulus (yes/no) and, if yes, where (left/right)?].

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Visuospatial cues were predictive of the location of the subsequent somatosensory target (the above mentioned near-threshold electrical pulse delivered to the right or left cheek). Hence, they indicated with a high probability (75% of the cases) the side of the face to which the somatosensory target would be delivered. Of all target-present trials, 75% were "valid" (the location of the delivered electrical pulse (either the right or left cheek) was predicted by the location of the cue on the computer screen (right or left side of the fixation cross), whereas 25% were "invalid" (the location of the delivered electrical pulse was not predicted by the location of the cue on the computer screen, hence delivered in the opposite participant's cheek).

Moreover, the somatosensory target consisted of either one (85% of the target-present trials) or two (15% of the target-present trials) weak electrical pulses. Only responses for trials in which the electrical pulse was delivered only once or was absent (catch trials) were considered in the analyses. Trials in which the electrical pulse was delivered twice served to control for response anticipation in the discrimination task. Seventeen percent of the total number of trials did not include any electrical stimulation (target-absent trials). In sum, out of 504 trials carried out on each of the two testing sessions, each participant completed 88 target-absent trials; 264 valid and 88 invalid trials in which the near-threshold somatosensory target consisted of a single electrical pulse; and 48 valid and 16 invalid trials in which the near-threshold somatosensory target delivered two electrical pulses.

Following target delivery, participants were asked to perform sequentially two tasks in response to it. First, they were asked (1st task of the behavioral paradigm) to report whether they felt in their cheek a single ("one") or a double ("two") electrical pulse (*discrimination task*) by pressing the corresponding key on a computer keyboard (either "1" or "2") with the index and middle fingers of their right hand. Participants were encouraged to respond as fast and as accurately as possible and to guess a response even when the somatosensory target was not delivered or if they did not consciously perceive it (forced-choice response). Visuospatial cueing effects on somatosensory discrimination were evaluated by measuring the reaction time to correctly discriminated and correctly detected targets.

Then participants were asked to report whether they had consciously perceived the somatosensory target or not (2nd task of the behavioral paradigm: *conscious detection task*). To do so, two arrow-like stimuli (">>>" and "<<<") pointing to the left and to the right were simultaneously presented below and above the fixation cross on the computer screen. Participants were provided with 3 keys, which they had to press with their left hand: an upper key "d", a lower key "c" and the space bar. The upper and lower keys were associated to the cheek location (right or left) pointed by the arrow presented on the top and the bottom of the screen, respectively. Participants had to respond by pressing the space bar if they did not feel the stimulus, or use the given key ("d" or "c") to select the upper or lower arrow pointing to the side

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of their face (left/right cheek) in which they perceived the somatosensory target. To avoid preparation of a motor response before the conscious somatosensory detection question was presented on the screen, the location of each arrow (above or below the fixation point) was randomized across trials.

2.5. Data analysis

The effect of visuospatial cueing on the discrimination task (1st task) was evaluated with the reaction time for correctly discriminated targets. However, this analysis included only trials in which the location of the target had been accurately determined according to the conscious detection task (2nd task of the behavioral paradigm). This was done since no accurate discrimination could be reliably performed on somatosensory targets that were later in the trial reported as not consciously perceived (hence discriminated randomly during the 1st task of the behavioral paradigm). In order to test this, we also calculated the reaction time for both valid (correctly predicted by a cue) and invalid (incorrectly localized by a cue) trials that were not consciously detected (where the somatosensory target was present but was not detected by participants) with paired t-test.

The effects of visuospatial cueing on the somatosensory conscious detection task (somatosensory target perceived? “yes” or “no” and if “yes”, where? “right” or “left” cheek) were assessed by means of two Signal Detection Theory outcome measures: perceptual sensitivity (d′) and response bias (beta). Perceptual sensitivity is a measure that informs on the participants’ ability to detect weak signals in situations that might be strongly influenced by belief. Response bias describes the relative preference of participants for one response over the alternative one, independently on signal strength (Green and Swets, 1966; Macmillan and Creelman, 2004).

To compute these measures, trials in which the location of a somatosensory target was correctly determined were considered as correct detections or “hits”, while trials in which participants reported a location for a somatosensory target that was not delivered (target absent) were considered as “false alarms”. Trials in which present-targets were incorrectly located were counted as “errors” and excluded from the analyses given that we could not rule out whether participants correctly perceived the stimulus but pressed the wrong key (the location of the arrows changed randomly across trials) or they incurred into a genuine mistake of somatosensory conscious detection. False alarms, hits and errors were calculated based on participant responses only for the somatosensory conscious perception task (2nd task). Perceptual sensitivity (d′) was computed from the hit rate and the false alarm rate: Z_{FA}-Z_{HIT}, where Z corresponds to the z-scores of the two rates. These scores were calculated using the inverse cumulative distribution function in Microsoft Excel 2007 (NORMSINV). Response bias (beta) was computed using the normal distribution function in Microsoft Excel 2007 [NORMDIST(Z_{HIT})/NORMDIST(Z_{FA})]. Moreover, an additional analysis was carried out to look at the correlation between

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the number of false alarms (based on the second task) and correctly discriminated targets (based on the first task) in order to confirm that the performance in the 1^{st} task (which by design is a forced-choice somatosensory discrimination) did not influence the level of false alarms in the 2^{nd} task (somatosensory conscious detection).

All three main outcomes (reaction time, perceptual sensitivity and response bias) were subjected to a 2 × 2 repeated measures ANOVA with trial validity (valid, invalid) and testing session (1^{st} session, 2^{nd} session) as within-participant factors.

3. Results

3.1. Errors

The ANOVA performed on errors (6 ± 5% of 'detected' somatosensory targets) yielded a main effect of validity ($F(1,14) = 15.41$, $p = 0.002$), indicating that participants made more errors in invalid trials (cue presented in the opposite screen side compared to the electrically stimulated cheek) than valid (cue presented in the same side as the electrically stimulated cheek) trials. No significant effect was found for the main effect of testing session or the interaction between session and trial validity.

3.2. Reaction time (somatosensory discrimination task)

Participants' mean reaction time for correctly detected target trials across conditions was 673 ± 73 ms (mean ± SD) (Table 1). The repeated measures ANOVA revealed a main effect of validity ($F(1,14) = 100.22$, $p < 0.001$), indicating that, as expected, participants were faster in responding to validly cued as compared to invalidly cued trials (Fig. 2). Additionally, there was a significant main effect of session (F (1,14)

Table 1. Reaction time (ms) for correct responses in the *somatosensory discrimination* task, and perceptual sensitivity (d′) and response bias (beta) for the *conscious somatosensory detection* task (mean ± SD). Data are provided for each experimental cueing condition and for the two sessions of testing. Notice that reaction times for the *somatosensory discrimination task* (1^{st} task of the behavioral paradigm) were calculated only for somatosensory targets that were correctly detected on the *somatosensory conscious detection task* (2^{nd} task of the behavioral paradigm).

	Somatosensory Discrimination Task		**Conscious somatosensory detection task**			
	Reaction time (ms)		**Perceptual sensitivity**		**Response bias**	
	Invalid	**Valid**	**Invalid**	**Valid**	**Invalid**	**Valid**
Session 1	762 ± 98	692 ± 77	2.4 ± 0.6	2.7 ± 0.6	18 ± 7	14 ± 8
Session 2	654 ± 110	583 ± 92	2.3 ± 0.5	2.5 ± 0.5	18 ± 6	13 ± 8

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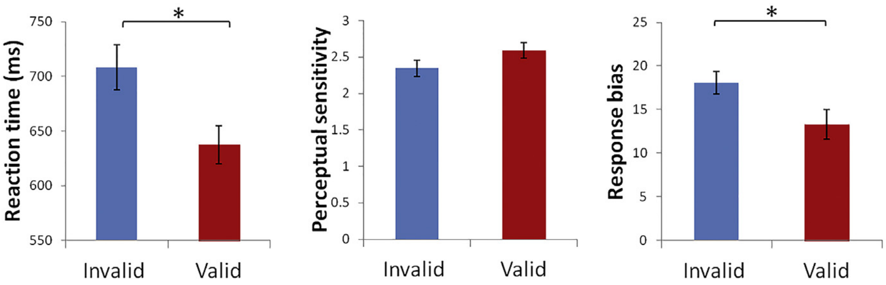

Fig. 2. Effects of spatial attention on somatosensory perception. The left panel shows reaction time for the discrimination task. The right panels show perceptual sensitivity and response bias for the conscious detection task. Notice that visuospatial attentional orienting decreased reaction time for the somatosensory discrimination task (1st task of the behavioral paradigm) and decreased response bias turning participants less conservative to acknowledge the delivery of a somatosensory target for the somatosensory conscious detection task (2nd task of the behavioral paradigm). A marginally significant improvement of perceptual sensitivity was also found. Asterisks indicate significant main effect of validity ($p < 0.05$).

Table 2. Repeated-measures ANOVA results showing p and F values for the main effects of factors 'validity' and 'session' and the interaction 'validity' * 'session' for each outcome measure. Notice that Reaction Times serve to assess cueing effects on *somatosensory discrimination* (1st task of the behavioral paradigm), whereas Signal Detection Theory measures, perceptual sensitivity (d′) and response bias (beta) gauged cueing impact on the *conscious somatosensory detection task* (2nd task of the behavioral paradigm).

	Somatosensory Discrimination Task		Conscious somatosensory detection task			
	Reaction Time (ms)		Perceptual Sensitivity		Response Bias	
	p-value	F	p-value	F	p-value	F
Validity	<0.001	100.22	0.060	4.19	0.008	9.45
Session	0.003	13.25	0.240	1.53	0.890	0.02
Validity*Session	0.944	0.01	0.862	0.03	0.826	0.05

= 13.25, p = 0.003) indicating that participants responded faster during the second testing session, compared to the first one. The interaction between factors 'session' vs. 'validity' did not reach significance (Table 2). Comparison of reaction times for valid and invalid trials in which the target was not consciously detected (where the somatosensory target was present but was not detected by participants) revealed no significant difference (valid = 561.8 ± 203.9, invalid = 556.3 ± 193.2, p = 0.69, paired t-test).

3.3. Perceptual sensitivity and response bias (somatosensory conscious detection task)

In the conscious detection task, participants' perceptual sensitivity (d′) across conditions was 2.5 ± 0.4 (mean ± SD) and their response bias (beta) was 16 ± 5 (mean ±

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SD) (Table 1). The low rate of false alarms explains the relatively high values observed for both perceptual sensitivity and response bias, even though according to the titration only ~62% of presented somatosensory targets were consciously detected correctly. Also there was no significant correlation (correlation coefficient = −0.25, $p = 0.19$) between the number of false alarms in the somatosensory discrimination task (2nd task) and the number of correctly discriminated somatosensory targets (1st task), suggesting that the performance in the 1st task did not influence the level of false alarms in the 2nd task (somatosensory conscious detection task). The repeated measures ANOVA for response bias (beta) revealed a significant main effect of validity ($F(1,14) = 9.45$, $p = 0.008$), indicating that participants had a less strict criterion in valid vs. invalid trials (Fig. 2). Similarly, the ANOVA for perceptual sensitivity revealed a main effect of validity that was marginally significant ($F(1,14) = 4.19$, $p = 0.060$), indicating a trend towards higher scores for valid as compared to invalid trials (Fig. 2). The main effect of session and interaction of validity vs. session for both response bias and perceptual sensitivity did not reach statistical significance (Table 2).

4. Discussion

We explored the effects of spatial attention on conscious perception of near-threshold somatosensory stimuli in a cross-modal cueing paradigm. The cue used to orient participants' spatial attention was a lateralized predictive visual cue, similar to that used in previous studies (Chica et al., 2011), presented on a computer screen in front of the participant. The somatosensory target consisted in brief near-threshold electrical pulses delivered to the left or right cheek, which only a few studies have investigated to date (Clery et al., 2015; Soto-Faraco et al., 2005).

In the *somatosensory discrimination task* of our behavioral paradigm, participants responded significantly faster for valid trials (in which the visuospatial cue correctly signaled the side of the face on which the target was delivered) as compared to invalid trials (in which the visuospatial cue signaled a position opposite of that in which the target was delivered) for correctly discriminated and consciously perceived somatosensory targets. This outcome suggests that participants effectively used the spatial information provided by the visuospatial cue to orient their attention accordingly to the right or left cheek. These results are consistent with previous studies assessing the effects of attention on somatosensory perception using both supraliminal (Butter et al., 1989; Kennett et al., 2002; Spence and McGlone, 2001; Van Hulle et al., 2013) as well as near-threshold stimuli (Soto-Faraco et al., 2005) manipulated with somatosensory or visual cues. These studies showed that both endogenous and exogenous cues decrease reaction times when attention is oriented toward the location of the tactile stimuli. Similar studies on conscious perception have also identified a reduction of response reaction time in a forced-choice

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perceptual discrimination task as a reliable proxy of an effective engagement of spatial attention orienting (Chica et al., 2013; Chica et al., 2011).

In agreement with prior reports in the visual perception domain (Chica et al., 2011; Kennett et al., 2002), we found that visuospatial attention modulated conscious somatosensory perception and induced a decrease in response bias (beta). Indeed, participants showed a less conservative criterion when responding to validly cued than to invalidly cued somatosensory targets. This result might be indicative of an increase in confidence consciously acknowledging the presence and delivery location of stimuli following predictive visuospatial cues (Chica et al., 2011).

Unexpectedly, perceptual sensitivity (d′) for the conscious somatosensory detection task only showed a non-statistically significant trend toward improving perception of near-threshold electrical facial stimuli preceded by valid vs. invalid visuospatial cues. Multiple reasons could explain this outcome. First, we might have lacked the power to demonstrate a significant effect on visual sensitivity. Yet calculations using data from prior unimodal attentional orienting paradigms in the visual domain (Chica et al., 2011) showed that our cohort outnumbered these sample size estimations. Secondly, our study used a cross-modal cueing paradigm based on visuospatial cues to influence somatosensory perception. Previous studies showed that cross-modal engagement of spatial attention, as in our study, may yield weaker effects on conscious perception than unimodal paradigms (Chica et al., 2007) in which cues and targets share the same sensory modality. Additionally, even though we used a peripheral cue (carrying an exogenous component), our attentional manipulation may have worked predominantly as *endogenous*, since the cue could not be presented at the exact delivery location of the somatosensory target due to the cross-modal design. Prior work has suggested the need of an exogenous component for spatial attention to be able to efficiently improve perceptual sensitivity (Chica et al., 2011). On the other hand, since both the removal and the maintenance of endogenous stimuli have shown an effect on conscious perception elicited by exogenous stimuli (Chica et al., 2011), it has also been suggested that this attentional modality interacts with conscious perception through the modulation of exogenous attentional orienting. Similar to exogenous stimulation, endogenous stimulation can produce a ‘pop out’ or phasic alerting effect (Chica, 2011) which adds to the orienting effects driven by visuospatial cues. Moreover, consistent with our findings showing significant decreases of response bias (beta) but a non-statistically significant trend for the modulation of perceptual sensitivity (d′), evidence suggests a dissociation between endogenous and exogenous spatial attention; while exogenous attention produces an effect on early perceptual stages, endogenous attention influences later stages of processing which are more likely affecting the decision of where to respond (Chica et al., 2013). Lastly, it has been shown that the detection of tactile stimuli depends on whether or not the body site where stimuli are delivered are viewed (Tipper et al., 2001). To this regard, our results might have been affected

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by the fact that the electrodes delivering the somatosensory stimulation on the participants' cheeks might have been partially captured by their peripheral vision.

Our results are somewhat different from those of the two other studies also using cross-modal paradigms with near-threshold tactile stimuli. Soto-Faraco et al. (2005), who assessed the effects of uninformative social attention cues on near-threshold tactile stimuli, showed that only reaction time and perceptual sensitivity, but not response bias, improved with validly cued stimuli (Soto-Faraco et al., 2005). Similarly, Clery et al., 2015 found that visual looming approaching the face could improve tactile sensitivity on the same side of the face as measured by improvements in perceptual sensitivity (Clery et al., 2015). The discrepancy between these studies and ours could be due to differences in the cueing paradigms (e.g. peripheral vs. central cues and informative vs. non informative cues) leading to the engagement of endogenous and exogenous attentional mechanisms at different levels.

Our findings extend prior unimodal attentional studies on the visual modality (Chanes et al., 2012; Chica et al., 2011) and show that visuospatial attention can modulate conscious access for near-threshold somatosensory stimuli. Taken together, our results argue also in favor of a relevant role of attention on conscious perception, which is in accordance with recent theories of conscious access that suggest top-down amplification (*via* long-distance connections and reverberating networks), as well as vigilance and bottom-up activation, as requirements for conscious perception (Dehaene et al., 2006). In this context, orienting attention endogenously (*top-down*) might improve conscious perception by decreasing response bias; however, this may not be sufficient to cause significant changes in perceptual sensitivity, particularly dependent on exogenous contributions, due to limitations in bottom-up stimulus strength. Future comparative studies using purely exogenous (i.e., non-predictive peripheral cues, with a 50% validity) and purely endogenous (i.e., predictive central) cues are needed in order to better understand how these two attentional components contribute to conscious somatosensory perception.

5. Conclusion

We showed significant effects of visuospatial attention on conscious perception for near-threshold somatosensory stimuli, as measured by shorter reaction times in somatosensory discrimination and a decrease in response bias (making participants apply a less conservative criterion). Our study is among the few that combined near-threshold somatosensory stimuli with predictive peripheral visuospatial cues, contributing important preliminary data to the literature. Our results are consistent with previous reports (Chanes et al., 2012; Chica et al., 2011) showing that visuospatial attention modulates conscious perception of near-threshold visual stimuli, an observation that importantly can be now extended to conscious perception in the somatosensory modality.

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Nonetheless, taken together with prior studies on the conscious visual perception domain (Chanes et al., 2012; Chica, 2011), our findings also provide support for sensory-modality dependent mechanisms subtending modulations of conscious access with visuospatial attention. Indeed, under predictive visuospatial cues, prior research has shown increases of perceptual sensitivity (d′) for near-threshold visual targets, leaving response bias (beta) unchanged, an outcome likely subtended by a top-down modulation of stimulus input-gain in primary visual areas (Chanes et al., 2012; Chica, 2011). In contrast, with identical cuing strategies and equally titrated near-threshold targets, our study now reports that using a very similar design decreases response bias (beta), in absence of perceptual sensitivity (d′) modulation, an outcome likely subtended by an impact of visuospatial attention on decision-making criterion processes.

Further experiments will be able to extend similar discrimination and conscious detection observations to additional sensory modalities (such as auditory) in both cross-modal and unimodal paradigms, and compare potential differences between exogenous vs. endogenous attentional components of cueing manipulations within these modalities.

Declarations

Author contribution statement

Deniz Doruk, Lorena Chanes, Alejandra Malavera, Felipe Fregni: Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; and wrote the paper.

Lotfi Merabet, Antoni Valero-Cabre: Conceived and designed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; and wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

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Additional information

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