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# The impact of focused attention on bilateral sensory threshold adaptation during unilateral short-term tactile stimulation

## Uticaj usmerene pažnje na bilateralnu adaptaciju senzornog praga nadražaja tokom jednostrane kratkotrajne taktilne stimulacije

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## Abstract

**Background/Aim.** Neuroplasticity of the somatosensory system can be manifested after short-term or long-term peripheral tactile stimulation. Focused attention has been well established as a modulator of neural processing in the visual and auditory systems. However, its role in the primary somatosensory cortex is insufficiently elucidated. The aim of this study was to examine the effect of focused attention on short-term somatosensory neuroplasticity following repeated tactile stimulation of different intensity over identical locations on the hands and shoulders. The aim of the study was also to determine whether repeated tactile stimulation of different intensity in the shoulder area of the non-dominant hand leads to a reduction in the stimulus threshold and to assess whether similar changes occur in the contralateral, unstimulated shoulder somatotopically identical location. **Methods.** This study included 30 healthy volunteers of both sexes. The contingent negative variation (CNV) wave and the Go/NoGo paradigm for measuring reaction time were used to objectively register the stimulus threshold for light touch, before and after sensory stimulation. The CNV wave was registered within the paradigm with two known stimuli, the first of which was tactile and the second visual in the form of a green or red circle that appeared randomly on the screen. Peripheral sensory stimulation was conducted only over the non-dominant hand and shoulder using multiple series with 12 tactile stimuli of varying intensities. **Results.** The results showed statistically significant decrease in the stimulus threshold for light touch on both shoulders after tactile stimulation performed only on the non-dominant shoulder. In addition, whenever CNV waves were detected within the Go/NoGo paradigm, reaction times of the subjects were significantly shorter, which served as an objective validation of the initial detection of tactile thresholds before and after peripheral sensory stimulation. **Conclusion.** Short-term, unilateral tactile stimulation leads to bilateral, functional adaptation of the proximal regions of the upper extremities, which suggests interhemispheric homologous transfer within the somatosensory system, supporting the principle of somatotopic organization in somatosensory neuroplasticity.

**Key words:**
**cerebral cortex; electroencephalography; neuronal plasticity; sensory thresholds.**

## Apstrakt

**Uvod/Cilj.** Neuroplastičnost somatosenzornog sistema može se manifestovati nakon kratkotrajne ili dugotrajne periferne taktilne stimulacije. Fokusirana pažnja je dobro poznat modulator neuralne obrade u vizuelnim i auditivnim sistemima. Međutim, njena uloga u primarnom somatosenzornom korteksu je nedovoljno razjašnjena. Cilj rada bio je da se ispita efekat fokusirane pažnje na kratkoročnu somatosenzornu neuroplastičnost nakon ponovljenih serija taktilnih stimulusa različitog intenziteta na identičnim mestima na šakama i ramenima. Cilj rada je takođe bio da se utvrdi da li ponovljeni taktilni stimulusi različitog intenziteta u predelu ramena nedominantne ruke dovode do smanjenja praga nadražaja i da se proceni da li slične promene nastaju i u kontralateralnom, nestimulisanom ramenu, na somatotopski identičnoj lokaciji. **Metode.** U ovu studiju je bilo uključeno 30 zdravih dobrovoljaca oba pola. Talas kontingentne negativne varijacije (*contingent negative variation* – CNV) i *Go/NoGo* paradigma za merenje reakcionog vremena bili su korišćeni kako bi se objektivno registrovao prag nadražaja za lak dodir, pre i nakon senzorne stimulacije. CNV talas bio je registrovan u okviru paradigme sa dva poznata stimulusa, od kojih je prvi bio taktilni a drugi vizuelni u vidu zelenog ili crvenog kruga koji su se nasumično pojavljivali na ekranu. Periferna taktilna stimulacija bila je sprovedena samo na nedominantnoj šaci i ramenu, i to

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kroz više serija sa 12 taktilnih stimulusa različitih intenziteta. **Rezultati.** Rezultati su pokazali statistički značajno sniženje praga nadražaja za lak dodir na oba ramena nakon taktilne stimulacije sprovedene samo na nedominantnom ramenu. Pored toga, kada god su bili detektovani CNV talasi u okviru *Go/NoGo* paradigme, reakciona vremena ispitanika bila su značajno kraća, što je služilo kao objektivna potvrda detekcije praga nadražaja pre i nakon periferne senzorne stimulacije. **Zaključak.** Kratkotrajna, unilateralna taktilna stimulacija dovodi do bilateralne, funkcionalne adaptacije proksimalnih regija gornjih ekstremiteta, što sugeriše interhemisferični homologni transfer u okviru somatosenzornog sistema, podržavajući princip somatotopskog organizovanja u somatosenzornoj neuroplastičnosti.

**Ključne reči:**
**mozak, veliki, kora; elektroencefalografija; neuroplastičnost; prag nadražaja.**

## Introduction

Studies have shown that the organization of the somatosensory system is prone to prompt adaptation as a response to changes in peripheral input [1–3]. In most of them, a deafferentation model was used in which peripheral sensory afferents were either temporarily suppressed or permanently eliminated [4]. However, research employing electrical stimulation of peripheral nerves has also demonstrated the induction of cortical plasticity, even in the absence of afferent deprivation [5, 6]. Additionally, studies focusing on repetitive tactile stimulation of peripheral mechanoreceptors have reported enhancements in somatosensory function, confirming that various stimulation paradigms can induce training-related perceptual learning [5, 7].

One of the main questions in the research of somatosensory systems involves the role of attention. A previous publication showed that anticipating a stimulus can improve overall perception by amplifying relevant stimuli and/or suppressing irrelevant ones [8]. In the visual and auditory systems, attention has an important role in filtering out unwanted and facilitating relevant afferent information; however, the picture is less clear for the somatosensory cortex, for which there is still a scientific debate whether this occurs at the level of primary somatosensory cortex (SI), secondary somatosensory cortex (SII) or both [9, 10].

Studies have used different parameters and spatial-temporal characteristics in repetitive tactile stimulation protocols [5].

The aim of this study was to explore the effects of focused attention on short-term peripheral tactile stimulation of the somatosensory system using tactile cued attention training. We employed a psychophysiological research paradigm combined with electroencephalography (EEG) recordings, with specific aims: to determine whether short-term tactile stimulation can reduce touch thresholds at the shoulder, and to examine whether a similar change occurs on the contralateral, non-stimulated shoulder, potentially indicating interhemispheric sensory modulation.

## Methods

### *Participants*

Thirty healthy volunteers (9 males and 21 females) between 18 and 55 years of age [mean ± standard deviation (SD): 35.4 ± 8.9 years] participated in our study. Participants were recruited from the general population and provided a detailed explanation of the study protocol before enrollment. We included subjects of all ethnic groups who could comprehend and had intact and normal manual dexterity to perform specific tasks during this research. According to the modified Edinburgh scale, 4 participants were left-handed and 26 had right-hand dominance [11]. All subjects self-declared that they had no prior history of any neurological, psychiatric, or cognitive impairment that might interfere with somatosensory perception and study interpretation. This study was approved by the Institutional Review Board of NYU School of Medicine, New York, USA (No. i14-01734; from January 13, 2015). Before participating, all volunteers provided written informed consent following the Declaration of Helsinki. All participants completed the study with no adverse events.

### *Location and experimental conditions*

The measurements were conducted at the Clinical Neurophysiology Laboratory at the Hospital for Joint Diseases, NYU Langone Health, New York, USA. The temperature of the testing environment was maintained at a comfortable 25 ºC. To ensure consistency across participants, all experimental recordings were performed at a time of day when each participant reported feeling most alert and focused. All experimental testing was conducted in a single session lasting approximately 4 hrs. Participants were asked to abstain from consuming any psychoactive substances, such as caffeinated drinks and/or alcohol, at least 24 hrs before the measurements took place [12, 13].

### *Equipment*

A tactile stimulator, TS 120 (SBMEDIC Electronics, Solna, Sweden), served as a generator of light touch. The actual tactile stimuli were delivered by a flat, round, 2 mm diameter plastic tip with blunt edges within the displacement-controlled system of the stimulator. The plastic tip had an adjustable displacement range of 1 µm to 1 mm with a resolution of 1 µm. Its duration of stimulation was 80 milliseconds (ms), and the speed of skin indentation was between 80 and 100 µm/ms. An EEG recorder (Nicolet Biomedical, Madison, WI, USA) was used for the registration of contingent negative variation (CNV) waves, and a desktop computer with the open-source application PsychoPy version 2020.1.2 (Open Science Tools Ltd., Nottingham, England) provided the recording of reaction time (RT) after the Go/NoGo decision task paradigm with dissimilar visual stimuli. The tactile stimulator and desktop computer were connected to an EEG recorder, which was a signal generator in this closed circuit.

### *Experimental design*

Recordings were conducted on four target locations: the thenar eminence and the lateral shoulder region bilaterally. Before all measurements, a participant took the most comfortable sitting position in an adjustable reclining chair. The arm upon which the trials were conducted was placed in a vacuum fixation pillow (AB Germa, Kristianstad, Sweden), which secured a stable position during the experiment. A mechanical multi-jointed device (Foba AG, Wettswil, Switzerland), to which the head of the tactile stimulator was attached, permitted fixation at any desired position and angle in relation to the skin surface. To ensure permanent contact during interval displacements of the stimulating probe tip, the probe was placed perpendicularly to the skin surface with constant indentation of approximately 1–3 mm. Over the range of amplitudes needed to activate skin mechanoreceptors of the shoulder, the head of this stimulator produced a sound that could have affected both CNV and RT recordings during light touch stimuli trials. To avoid this confounding element, all participants wore noise-canceling headphones (Bose, Framingham, MA, USA) through which a computer-generated pink noise with a sufficient volume to mask all surrounding room noise was generated. Before measuring the shoulders, we conducted a two-point discrimination test using an aesthesiometer (Healthcare Fitness Products, Cottage Grove, WI, USA) to determine the width of the mechanoreceptor fields [14]. Volunteers were asked not to move or blink their eyes except between trials.

### *Contingent negative variation and reaction time recordings*

To objectively assess light touch perception, we used the CNV paradigm as a quantitative psychophysiological procedure [15, 16]. The CNV traces were recorded with gold cup surface electrodes (Natus Medical Incorporated, Middleton, WI, USA) placed according to the international 10–20 system. Before placing the electrodes, we prepped the skin with alcohol and abrasive gel, and to decrease impedance, we used conductive paste (Weaver and Company, Houston, TX, USA). We used midline central (Cz), frontal left (F3), frontal right (F4), and left mastoid as recording electrodes, while the midline frontal (Fz) electrode served as a reference. The ground electrode was placed on the forehead. Electrode impedances were kept below 5 kiloohm (kΩ), and the evoked potentials were recorded with a filter bandwidth of 0.2 Hz to 30 Hz. The CNV was recorded by applying a tactile stimulus followed by a visual stimulus with a one second interval between them, during which CNV was generated. For each stimulating tip displacement value, a pair of tactile-visual stimuli were administered 12 times, and all CNV traces were averaged and recorded during one trial [16]. The averaged CNV amplitudes in microvolt (μV) were measured for each trial, and inter-trial intervals varied randomly from 3 to 8 s. The trial had no start cue, and participants waited for the new tactile stimulus after the last visual stimulus, therefore maintaining their focused attention during the experiment. The participants were given a 3- to 5-min break after each location was tested to avoid mental fatigue, maintain concentration, and prepare the equipment for the following stimulation site. For the analysis of CNV waves, we assessed the presence of early CNV (eCNV) and/or late CNV (lCNV) wave components. An early component was determined based on the individual maximum amplitude between 350 and 650 ms after tactile stimulus, and a late component with a maximum amplitude in a 200 ms interval preceding visual stimulus [17]. All CNV amplitudes were calculated offline after the measurements were done. During the recordings of all trials, we subjectively determined only the presence or absence of CNV responses. CNV recordings containing eye movement, blinking, or facial muscle artifacts were excluded from further analysis. RTs were recorded using the Go/NoGo paradigm, randomly providing one of the two dissimilar visual stimuli (green or red). Either a green or red circle was automatically shown on a computer screen, placed approximately 1.5 m in front of a subject, precisely one second after each tactile stimulus was exerted. Subjects were instructed to press the space key on a computer keyboard with the contralateral, non-stimulated hand as quickly as possible, only after the green light was shown on the screen, and to do nothing when the red light appeared. The result of this action was a measure of their RT in milliseconds, which was the period between the onset of visual stimulus and pressing the keyboard. The basic concept of the CNV paradigm and the study design were thoroughly explained to the subjects before the trials began. The sequence of the CNV paradigm and Go/NoGo decision task model is summarized in Figure 1.

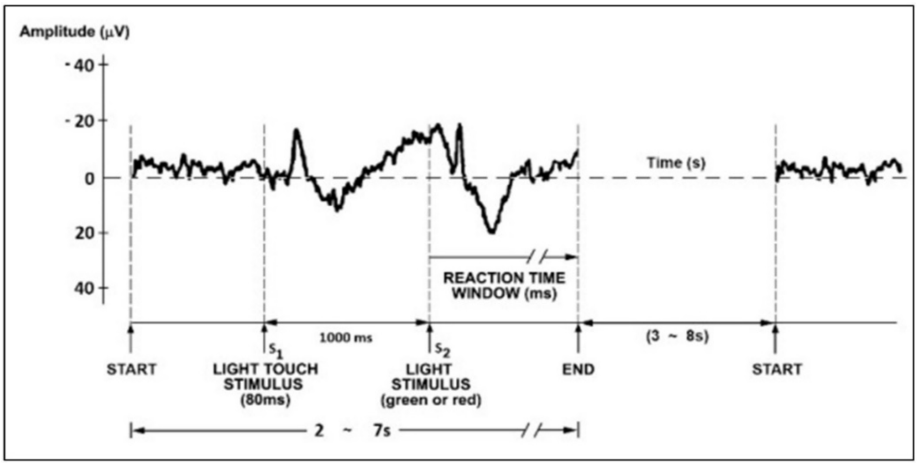

**Fig. 1 – Schematic representation of the CNV paradigm and the Go/NoGo decision task model. CNV– contingent negative variation; S1– tactile stimulus; S2 – visual stimulus.**

### *Determination of baseline tactile thresholds*

To determine light touch thresholds, we tested the thenar eminence and shoulder of the non-dominant arm, followed by the thenar eminence and shoulder of the dominant arm, with the assessment of CNV and RT. For the initial threshold determination procedure, we used the method of descending levels, which utilizes stimuli of predetermined levels of intensity and duration [18]. The first displacement of the stimulating tip was set to a value well above the expected perception threshold of the tested skin region (50 µm and 150 µm for the thenar and shoulder, respectively), with the step size of changes in the intensity of tactile stimulation of 2 µm for the thenar and 20 µm for the shoulder. A set of 12 stimulations *per* trial was delivered, with one to three second of pseudorandom delay between stimulations, and CNV with RT values were recorded. After every stimulus, a participant was asked to report whether a tactile stimulus was perceived, and this process was repeated, with a subsequent decrease of stimulating tip amplitudes for every trial, until a participant reported feeling 6 to 8 touches out of 12 repetitions. The touch threshold was considered the displacement of the stimulating tip (in µm), which still produced a clear CNV recognizable in the record, even if it was of lower amplitude than the CNV related to stronger stimuli [16]. The same approach was repeated for the measurements over other locations as well.

### *Peripheral sensory stimulation and determination of new tactile thresholds*

Peripheral sensory stimulation was conducted over the lateral shoulder surface of the non-dominant arm only. To avoid confounding results within the Go/NoGo RT paradigm, participants had to use their dominant hand to press the keyboard. We used the exact positioning of participants and equipment and the same concept of the CNV paradigm and Go/NoGo decision task compared to determination of baseline tactile threshold. Regarding the stimulus intensity, we started from the confirmed threshold levels and then randomly stepwise changed the displacement of the stimulating tip up and down, with an overall decrease of stimulating amplitudes toward sub-threshold levels. The step size change was 20 µm, identical for all 30 participants. On average, before reaching new tactile thresholds for all participants, we had to repeat 6 to 8 trials of 12 tactile stimuli. When the CNV was obtained, the lowest stimulus intensity was taken as a new objective threshold for light touch on the stimulated shoulder.

### *Tactile threshold assessment of non-stimulated shoulders*

After a series of peripheral sensory stimulations, we assessed whether any changes occurred for the contralateral (non-stimulated) shoulder. The setup of the equipment and participants was the same, except here, we performed only two trials with 12 stimulus repetitions, as we wanted to avoid the effects of direct peripheral sensory stimulation on this shoulder. For these two trials, we used levels of tactile stimulus intensity comparable to when we recorded a new touch threshold over the non-dominant shoulder. If the CNV was acquired during the first trial, we took that as a new objective touch threshold over the non-stimulated shoulder. After that, we conducted a second trial with the tip displacement reduced by 20 µm to confirm the absence of the CNV at subthreshold levels of tactile intensity. On the other hand, if the CNV was not recorded during the first trial, we increased the tip displacement by 20 µm, then recorded clear CNV and took that level of tactile stimulation as the new threshold.

### *Statistical analysis*

Volunteers were assigned with record numbers only, and the following data parameters were recorded: gender, age, hand dominance, amplitude of stimulating tip displacement (in µm), CNV recordings (latency values in ms, amplitude values in µV), RT values within the Go/NoGo decision task paradigm (in ms) and number of subjectively perceived tactile stimuli. All statistical analyses were conducted using SPSS Statistics version 21. Results are given as mean values ± SD. To compare two means, a Student's *t*-test was used for independent or paired samples, with the statistical significance level set at $p < 0.05$. The one-way analysis of variance (ANOVA) and two-way repeated measures ANOVA were used to determine the differences with significance levels established at $p < 0.05$. Before applying ANOVA, Shapiro-Wilk's test was used to assess the assumptions of normality, and Mauchly's test of sphericity was used to test the homogeneity of variances. When necessary, a logarithmic transformation was applied ($p < 0.05$), and the procedure was repeated. The Student-Newman-Keuls method was used as a *post-hoc* test whenever the ANOVA revealed a significant difference between three or more sample means ($p < 0.05$). Bonferroni correction was used when several statistical tests were performed simultaneously. Spearman's rank-order correlation was used to determine the relationship between two parameters.

## **Results**

### *Determination of baseline tactile thresholds*

Mean values and SDs for baseline tactile threshold measurements (stimulating tip displacements in µm) are presented in Table 1.

### *Relationship of contingent negative variation and reaction time recordings before peripheral sensory stimulation*

Before peripheral sensory stimulation, CNV traces were present for all supra-threshold and threshold measurements. This relationship was confirmed with the *t*-test, which showed significant differences in the number of subjective verifications of light touch stimuli when the CNV traces were generated and when they were absent in all four locations we assessed [non-dominant thenar: *t* (88) = 30.74, $p = 0.0001$; non-dominant shoulder: *t* (88) = 34.57, $p = 0.0001$; dominant thenar: *t* (88) = 34.93, $p = 0.0001$; dominant shoulder: *t* (88) = 25.97, $p = 0.0001$]. The one-way ANOVA did not reveal statistically significant differences in CNV amplitudes between all four locations on which we conducted measurements for both supra-threshold ($F_{3,116} = 0.391$, $p = 0.761$) and threshold ($F_{3,116} = 0.018$, $p = 0.997$) levels of tactile stimuli.

Further analysis (Figure 2) demonstrated statistically significant shorter RT recordings when CNVs were present (non-dominant thenar: $F_{1,29} = 78.853$, $p = 0.001$; non-dominant shoulder: $F_{1,29} = 79.032$, $p = 0.001$; dominant thenar: $F_{1,29} = 80.575$, $p = 0.001$; dominant shoulder: $F_{1,29} = 56.387$, $p = 0.001$). Additionally, it was confirmed by one-way ANOVA that the applied intensity of touch stimuli significantly influenced the duration of RT recordings (non-dominant thenar: $F_{2,87} = 30.83$, $p = 0.001$; non-dominant shoulder: $F_{2,87} = 21.95$, $p = 0.001$; dominant thenar: $F_{2,87} = 16.02$, $p = 0.001$; dominant shoulder: $F_{2,87} = 19.51$, $p = 0.001$). After *post-hoc* analysis, we found significantly shorter RT recordings [non-dominant thenar: *t* (88) = 7.39, $p = 0.001$; non-dominant shoulder: *t* (88) = 6.65, $p = 0.001$; dominant thenar: *t* (88) = 5.51, $p = 0.001$; dominant shoulder: *t* (88) = 6.27, $p = 0.001$] during threshold and supra-threshold levels of tactile stimulation compared to trials when participants reported no sensation at all (Figure 3).

**Table 1**

**Values of stimulating tip displacement in micrometers (µm) for measuring baseline tactile thresholds**

| Location of measurement | Baseline tactile thresholds |
|---|---|
| Non-dominant thenar | 8.7 ± 1.6 (5–10) |
| Non-dominant shoulder | 75.3 ± 17.5 (40–100) |
| Dominant thenar | 8.3 ± 1.7 (5–12) |
| Dominant shoulder | 78 ± 20.1 (40–110) |

**Values are presented as mean ± standard deviation and range.**
**ANOVA: $p < 0.05$; *t*-test: $p < 0.05$**

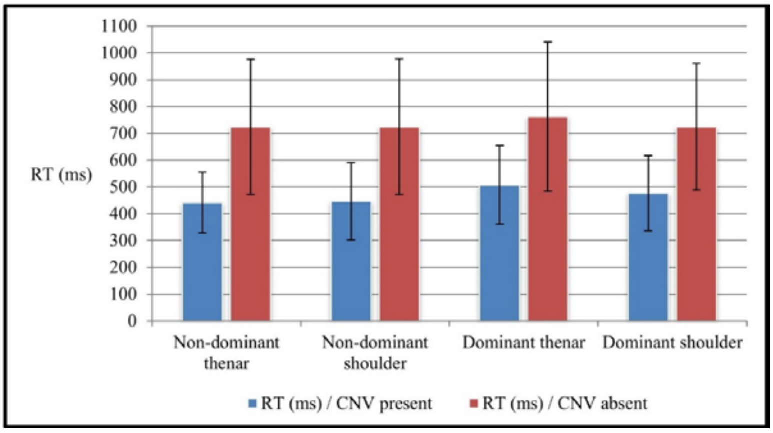

**Fig. 2 – Relationship between CNV amplitude and RT before peripheral sensory stimulation.**
**CNV – contingent negative variation; RT – reaction time.**
**Values are presented as mean ± standard deviation; *t*-test: $p < 0.05$.**

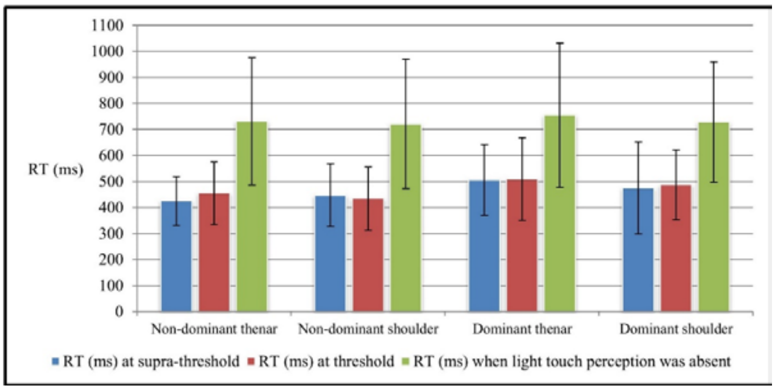

**Fig. 3 – RT recordings at different thresholds across all measurement locations.**
**RT – reaction time.**
**Values are presented as mean ± standard deviation; *t*-test: $p < 0.05$;**
***post-hoc* comparison for threshold and suprathreshold levels versus infrathreshold stimuli, $p = 0.001$.**

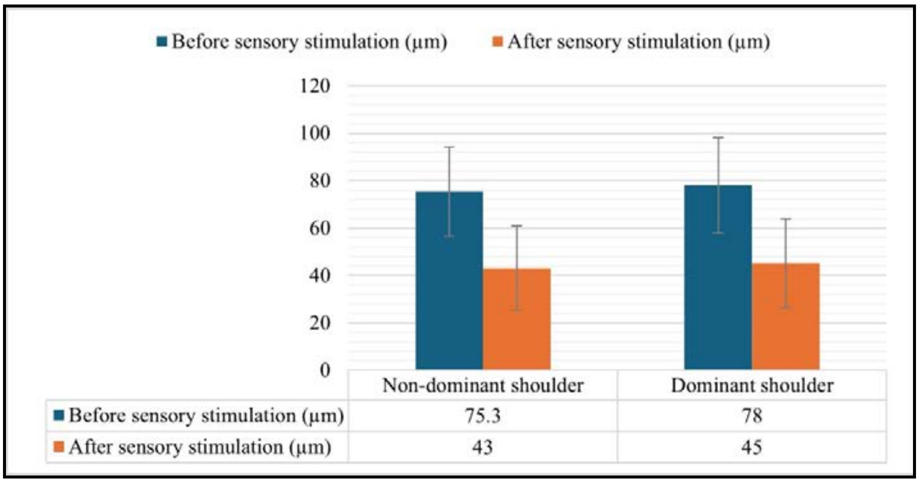

**Fig. 4 – Reduction in tactile thresholds following peripheral sensory stimulation. Values are presented as mean ± standard deviation; *t*-test: $p < 0.01$.**

*Determination of tactile thresholds after peripheral sensory stimulation*

Assessment of tactile thresholds after peripheral sensory stimulation conducted over the non-dominant shoulder showed changes on both shoulders in all 30 participants (Figure 4).

When we compared the data before and after sensory stimulation, we got a statistically significant decrease in tactile thresholds in both non-dominant ($F_{1,29} = 8.785$, $p = 0.006$) and dominant ($F_{1,29} = 227.591$, $p = 0.001$) shoulders. In addition to that, there was no statistically significant difference in the new tactile thresholds between both shoulders ($F_{1,29} = 1.812$, $p = 0.189$). After peripheral sensory stimulation, we evaluated the presence of new tactile thresholds on both shoulders with recordings of CNV traces and RT values. CNV waves were present for all 30 participants, with varying amplitudes. The analysis of the relationship between generated CNV traces and RT values showed results comparable to those obtained before sensory stimulation. Whenever participants generated CNV traces of any amplitude, their RT values were significantly shorter [non-dominant shoulder: $t\ (29) = 7.34$, $p = 0.001$; dominant shoulder: $t\ (29) = 5.98$, $p = 0.001$].

## Discussion

This study investigated the probability of tactile threshold changes after short-term peripheral sensory stimulation of skin mechanoreceptors.

*Tactile thresholds decrease on the stimulated shoulders*

Studies have shown that the processing of sensory inputs is not hard-wired but adapts to sensory experience. The adult cortex demonstrates reduced reorganization potential than during its developmental period, but still preserves the capacity for significant neuroplasticity [19, 20]. In addition to studies describing peripheral deafferentation as a model for investigating neural reorganization, experience-dependent neuroplasticity, and perceptual learning have emerged as frequently used paradigms for studying somatosensory changes at multiple levels [21]. Likewise, our study demonstrated a rapid and statistically significant change in somatosensory system processing after short-term sensory enrichment conducted at the exact location. The threshold of light touch changed from an average of 75.3 µm to 43 µm, a significant decrease of 32.3 µm on average over the area of stimulation. Other studies examining peripheral tactile stimulation in amputees have reported comparable changes, as seen in the publication by Dhillon et al. [22], where sensory input was presented to long-term upper limb amputees for only a short period (< 75 min throughout the study), resulting in enhanced sensory perception. That finding supported the view that the organization of the human brain is use-dependent and constantly adapting to demands and experiences.

The role of attentional engagement and behavioral relevance in sensory processing has been explored in studies on passive tactile co-activation, among others, some of which have yielded unexpected results. Ziemus et al. [23] investigated changes in the SI representation of the four fingers following a 40-min passive tactile co-activation task. Their results indicated a convergence of median and ulnar nerve cortical representations, implying that the cortical boundaries between activated regions moved closer together. However, they found no significant improvements in tactile perception, which they explained by the short duration of stimuli or lack of behavioral relevance in their experiment (subjects did not have to pay attention to the stimulation). On the contrary, Godde et al. [24] applied a co-activation task for three hrs, which was restricted to the tip of the right index finger, allowing simultaneous stimulation of all overlapping receptive fields. Even though participants in this study did not have to pay attention to stimulation, they found that several hrs of tactile co-activation protocol could improve perceptual performance. In this case, we might speculate that evident perceptual changes had occurred due to much longer tactile co-activation, which was focused on a single location with overlapping receptive field areas. Interestingly, the overall duration of peripheral stimulation in our setting lasted no more than 45 min. It was constantly delivered over the same receptive field on the shoulder area without co-activation. Compared to the most frequently used stimulation protocols [25], this duration of stimuli over the same receptive field, combined with behavioral-relevant study tasks, was sufficient to generate quick, adaptive changes in the somatosensory system in our experiment. For our study, the behavioral relevance of tactile peripheral stimulation was included in the Go/NoGo RT paradigm with dissimilar visual stimuli. The role of attention in cortex remodeling was clearly described [26]. We asked participants to remain attentive during the experiment and to focus on the tactile stimuli, which varied from supra- to sub-threshold intensities throughout the sensory enrichment we provided. Tactile stimulation served as a sensory preconditioning [27], combined with a goal-directed assignment in the Go/NoGo paradigm. Sensory preconditioning in this complex task was objectively confirmed by recordings of CNV, which reflects a tonic modulation of the EEG signal in the preparatory period between a warning signal (light touch, in our study) followed by a predictable and known interval before an imperative stimulus (visual stimulus, in our research) that cues an RT response [16]. We recorded a well-defined CNV where participants reported 6 to 8 perceived light touch stimuli in 12 repetitions, correlating with previously described data [16].

However, we did not register a significant difference between the CNV amplitudes before and after peripheral sensory training for both non-dominant and dominant shoulders. This implies that the intensity-response curve was not present in our CNV recordings. That was the expected result, which did not exclude the fact that whenever our participants felt light touch stimulation, they generated a CNV wave. In addition, we registered RT values that were functionally interconnected with CNV recordings, which served as another confirmation of light touch perception. Participants had faster RTs in the Go/NoGo paradigm task whenever they felt the tactile stimulation, compared with trials when the subjective perception of light touch was absent. In addition, we registered that whenever participants displayed an increased CNV amplitude, shorter RT was observed in that trial, but that correlation did not reach statistical significance. These findings suggest that participants were better prepared for the upcoming visual stimulus and motor response when tactile perception was heightened, demonstrating that a warning stimulus enhances response preparation and reduces RT, further reinforcing the functional interplay between tactile perception, attentional engagement, and motor response readiness.

### *Tactile thresholds decrease on opposite (non-stimulated) shoulders*

It is well established that sensory input from one limb primarily modulates the contralateral SI, which represents the stimulated limb. However, reports during the last two decades showed that tactile information from the periphery reaches SI in both hemispheres [28–30] and that alteration of sensory input may influence the excitability of the ipsilateral somatosensory cortex as well [29–31]. Interhemispheric transfer of tactile information is particularly important in higher primates and humans. The cortical regions of bilateral hand and arm representations integrate somesthetic input during the bimanual and cooperative exploration and discrimination of tactile features [32]. The idea that the SI receives input from the ipsilateral hand initially came from Tamura [33] several decades ago. That hypothesis led to many behavioral, electromyographic, transcranial magnetic stimulation (TMS), and functional magnetic resonance imaging studies, which addressed the similar question of anatomical connection and transfer of information between homotopic cortical and subcortical areas [22, 26, 30]. Our study examined whether unilateral short-term stimulation of a proximal upper limb area would also enhance sensitivity in the homotopic region of the contralateral upper extremity. We applied a quantitative psychophysiological approach, incorporating cortical anticipation measures as an indirect indicator, in which, after the short-term peripheral sensory stimulation over the lateral surface of the shoulder, we observed equal changes in the contralateral, symmetrically opposite location. Statistical analysis showed almost no difference in the new touch thresholds, 45 µm and 43 µm, for the dominant/stimulated and nondominant/non-stimulated shoulders, respectively. This finding indirectly supports interhemispheric interactions after relatively short peripheral stimulation. Previous studies by Frank et al. [34] and Frank [35] supported the existence of interhemispheric interactions between symmetrically opposite body surface areas, which are somatotopically organized, and confirmed that tactile learning in humans is topographically distributed [7, 34, 36]. These crossed interactions between limbs are likely mediated, at least partially, by the fibers of the corpus callosum [37, 38]. Highlighting the significance of transcallosal pathways in influencing the functional state of the ipsilateral SI, studies showed that applying TMS to the parietal cortex on the same side as the stimuli led to heightened tactile sensitivity. It was suggested that this effect was due to TMS interfering with typical interhemispheric inhibition, a mechanism that suppresses mirror movements in the passive limb during one-handed tasks [39]. The functional significance of interhemispheric inhibition deactivation is reflected in everyday activities when individuals depend on sensory input from the fingers of one hand to recognize various textures. During unimanual exploration, the texture typically affects all fingers of that hand similarly. However, in tasks involving bimanual manipulation, each hand may receive distinct sensory information [28]. Besides the proposed transcallosal connections, other points along the ascending and descending pathways, including subcortical structures and segmental networks, may be implicated in the functional coupling between the upper limbs [40].

Indeed, understanding the mechanisms and time reference of afferent tactile information processing through the cortical and subcortical networks of the somatosensory system is of great interest. The review by Chipchase et al. [5] on peripheral electric stimulation and the induction of cortical plasticity mentioned several possible mechanisms that are thought to underlie rapid plastic changes in the somatosensory cortex. These include the unmasking of latent horizontal connections, activation of silent synapses, modulation of activity-dependent synaptic plasticity, and generalized changes in the excitability of postsynaptic neurons. Another review [25] of tactile stimulation interventions reported that the transfer of plastic changes relies on the overlap of receptive fields and their cortical representations. Only if such an overlap is given among body parts can stimulation-induced effects spread between them.

In our study, the focused attention of all subjects could have represented an important additional factor for the short-term modulation within somatosensory system processing. Diminutive modifications of brain circuits and slight changes in synaptic strength across many neurons can be challenging to identify and measure. The contingent negative variation reveals sensorimotor integrative and preparatory processes, representing a long-latency, slow, and negative potential shift with cognitive and motor components [41]. It is present during response anticipation and was termed “expectancy wave” when it was first described by Walter et al. [15]. The CNV wave serves as an index of cortical arousal during orienting and attention and is related to higher mental functions involved in processing incoming sensory input [17], with high CNV amplitude indicating a high attentional state of a subject [42]. In addition, for the assessment of volitional inhibition or activation in neurophysiological studies, a Go/NoGo RT task has been frequently used [43, 44]. A Go/NoGo decision task model is based on the time required for a subject to respond and make a specific motor action to one class of stimuli (also known as the Go response) or to withhold from responding (the NoGo response) to a different stimulus type (decision of pressing a key for one stimulus while not pressing it for another stimulus). A study by Kropp et al. [17] showed that the negativity of the early CNV wave increased with decreasing RT, indicating that higher attentional involvement correlated with faster RT.

We might speculate that the influence of attention (top-down control) on the somatosensory system may involve gating and enhancing properties, depending on the task difficulty or the stimulus nature. Moreover, studies on animals and human subjects confirmed the existence of neurons in the postcentral gyrus with bilateral receptive fields in distal (hands) as well as in proximal parts of the body (upper arm, trunk), which might play a significant role in the somatotopic transfer of perceptual learning [7, 35, 45]. Harrar et al. [7] demonstrated that the generalization of tactile perceptual learning in hands was topographic, and the transfer was complete; topographically related fingers showed the same magnitude of improvement as the trained finger. Most importantly, investigations on human subjects [3] and experimental animals [46] confirmed that ipsilateral input can modify the SI and SII response to a subsequent contralateral stimulus.

The differences in communication between cerebral hemispheres and the spinal cord for proximal and distal muscle groups are well-documented [47]. Still, the similar effects of proximal limb somatosensory homologous transfer and its effect on bilateral communication, along with behavioral significance, have gained less attention. Aune et al. [48] investigated the hypothesis that bilateral learning transfer should be larger for proximal than for distal homologous effector muscles. They included 28 participants in three groups: training proximal effectors, training distal effectors, and a no-training control group. They found that both training groups showed similar improvements; however, the proximal training group exhibited greater transfer of learning than the distal one. Therefore, they concluded their hypothesis of a proximal-distal gradient in bilateral learning transfer between homologous effectors, suggesting that proximity to the body core may influence the extent of this communication. Similarly, our findings might raise the possibility that afferent signals from the repetitive shoulder stimulation modulated the response of the SI/SII upper arm region ipsilateral to tactile stimuli.

Without a doubt, more detailed studies are needed to elucidate this interesting question and offer further perspectives on how interhemispheric communication differs between proximal and distal limb somatosensory areas and how these differences might influence the transfer of learning.

## Conclusion

Our results indicate that short-term unilateral peripheral stimulation leads to equivalent reductions in tactile thresholds on both shoulders. These findings provide indirect evidence for interhemispheric transfer of simple tactile stimuli, aligning with the somatotopic organization of somatosensory processing.

## Conflict of interest

The authors declare no conflict of interest.

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