Reliability of tactile perception and suppression measurements

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Abstract

Tactile signals arising on one's own body allow estimation of one's own sensory state and foster interactions with the environment. However, tactile perception can be influenced by various factors. For instance, tactile perception is impaired on a moving than resting limb, a phenomenon termed tactile suppression. Here we examine whether tactile perception during resting and during movement is robust over shorter and longer time intervals. Participants had to detect tactile stimuli of various intensities on their index finger while this finger was resting or moving (finger extension). This detection task was performed on four separate days across a period of one month. We found that tactile perception during resting is robust within single sessions and across days. However, tactile perception during movement was poorer with more exposure to the task, both within and across sessions. Nevertheless, equivalence testing shows that this poorer sensitivity during movement as a function of time cannot explain the phenomenon of tactile suppression reported in the literature. The implications of these findings for wearable haptic interfaces are discussed in light of time-related changes in tactile suppression.

Keywords

detection thresholds, tactile adaptation, temporal effects, tactile gating

Introduction

Tactile signals provide humans with the ability to feel and successfully interact with their surroundings as these signals convey information about the properties of the environment and of one's own movements (for a review, see [1]). For example, humans can use signals from their touch receptors to identify properties of surfaces and objects with which they interact, such as temperature [2], friction [3], edges [4] or shape [5]. In addition to perceiving the surrounding world, tactile signals are important for motor behavior, for instance by fostering the sense of body position [6] and by detecting object slippage during grasping [1]. Considering these, it may appear as a paradox that tactile sensitivity is suppressed on body parts just before and during voluntary movement [7-10]. This is reflected in the reduced perception of identical tactile stimuli on a moving compared to the same but resting limb.

This phenomenon in tactile perception, called tactile suppression, is evident in various human actions, such as simple finger [11] or stroking movements [12], reaching [10], grasping [8], and even during whole-body tasks such as balance retention [13, 14]. Suppression is thought to result from a hybrid feedforward-feedback mechanism that integrates prior knowledge about the underlying dynamics and sensory feedback to release a motor command, through which the brain can estimate the upcoming sensory states of the body [15]. This estimate is compared with the actual sensory feedback, and those signals that match the prediction are suppressed. Consequently, just preparing to execute a voluntary movement can lead to tactile suppression on the body part that is planned to move, even if it eventually does not move [16, 17]. Likewise, tactile suppression is stronger during active than passive movements [18], likely because the latter are assumed to lack a feedforward motor command, and thus being unable to generate predictions about the sensory states of the passively moved limb. However, the fact that passive movements do lead to tactile suppression, albeit to a lesser extent than active ones [18], is taken as evidence that other, non-predictive, mechanisms may also be involved in this phenomenon [19].

A common way to assess tactile perception in general, and tactile suppression specifically, is to conduct psychophysical experiments and estimate tactile detection [20, 21] or discrimination [10, 22] thresholds, or tactile sensitivity using signal detection measures [8,

18]. Typically, tactile perception is quantified while participants are in rest, and the effects of motor processes on perception are examined while participants perform the instructed movements (e.g., [20, 21]). The resting and moving conditions are often presented in separate, counterbalanced blocks of several (>50) trials (e.g., [20, 21]), or in a single block with resting and moving trials being presented randomly and interleaved (e.g., [18]). In either case, experimenters estimate tactile sensitivity in each of the resting and moving conditions to assess the effect of movement on tactile perception.

Repetitive exposure to sensory stimuli can have consequences on perception itself. These consequences can be observed as decline or enhancement of perceptual performance with repeated exposure to the task and may arise from perceptual learning or sensory adaptation. Specifically, perceptual performance can be sharpened with repeated exposure or training (for a review see [23]), which can lead to improved detection of tactile stimuli with more exposure to the task. Meanwhile, repeated exposure to a stimulus can sometimes lead to adaptation of the activated tactile receptors and the underlying neural pathways, which can in turn lead to an exponential decrease in sensitivity, at least when testing tactile detection after various intervals following suprathreshold stimulation [24, 25]. Perceptual learning and tactile adaptation can have implications in the assessment of tactile perception and tactile suppression. In the context of perceptual learning, tactile sensitivity may improve with more exposure to the stimuli, and thus perception may be better at the end of an experiment. In the context of adaptation, tactile sensitivity may decrease with more exposure to stimuli, and thus perception may be poorer toward the end of an experiment. Some studies ruled out this possibility by testing potential differences in tactile perception between the early and late parts of the experimental procedure, with the comparisons typically showing consistent tactile performance at rest, at least when the tested periods were up to ~30 min [26] and ~90 min [27]. To the best of our knowledge, no study systematically assessed temporal effects on tactile perception and suppression over time, both within and across days. This is important because the reported effects of tactile suppression may be affected by such temporal effects that might require a re-interpretation of previous results.

We here examined whether tactile perception and suppression change following systematic exposure to tactile stimuli over longer time periods of up to one month. Human participants performed a detection task in which tactile stimuli were delivered to their index

finger while their hand was resting or actively performing a finger extension. The experiment consisted of four sessions performed on four different measurement days. Each session comprised 12 mini-blocks; six mini-blocks with the hand resting and another six mini-blocks with the hand moving. We assessed tactile perception in each of these mini-blocks for each measurement day separately. If tactile perception is influenced by perceptual learning or adaptation processes, we expect to see improved or worse sensitivity over time, respectively. If tactile perception is robust over time, we expect no change in performance (equivalence testing for null hypothesis).

Methods

Participants

Twenty-six healthy adults participated in the study, but due to technical issues, our final sample comprised 24 adults (18 females, age range: 19-33 years; 6 males, age range: 20-35; mean age: 21.8 years old). All participants were recruited from the university pools of Justus Liebig University Giessen and were screened for right-handedness using the German translation of the Edinburgh Handedness Inventory ([28]; mean EHI score: 91; EHI range: 69-100). After providing a detailed explanation of the study procedure, written consent was obtained from all participants. The study was approved by the local ethics committee of Justus Liebig Universität Giessen and was conducted in accordance with the Declaration of Helsinki (2013; except for §35, pre-registration). Participants received compensation in the form of 8 euros per hour or course credits for their involvement in the study.

Apparatus and setup

Participants sat in front of a table with their right index finger resting on a button box and their left hand positioned on a response keyboard. Brief (50 ms, 250 Hz) vibrotactile stimuli varying in intensity (peak-to-peak amplitude of 6, 12, 19, 25, 31, 38 µm) were transmitted using a custom-made vibrotactile device (Engineer Acoustics Inc., Florida, USA) to the dorsal part of the right index finger's proximal phalanx. An Optotrak Certus system (NDI, Waterloo, Ontario, Canada) was used to record the position of a single infrared marker attached to the participant's right index fingernail at 100 Hz. Participants indicated their detection response to the tactile stimulus in each trial by pressing a key on the keyboard using their left hand.

Procedure

Participants attended four measurement sessions over a span of four separate days, following a specific timetable: the second session occurred the day following the initial measurement, the third session took place seven days after the first measurement, and the fourth session was performed thirty days after the initial session. We took care that each participant's session took place on roughly the same time of the day across the four measurement sessions. Upon arrival to the lab on each measurement day, participants were given time to settle into a comfortable seated position. Their left hand rested on a table ~30 cm in front of their chest and 20 cm to the left of their body midline, positioned on the response keyboard, while their right hand rested on the button box situated ~30 cm in front of them and 20 cm to their right of their midline. Hand placement was customized for individual comfort, taking into account variations in arm, hand, and finger lengths. Participants then performed twelve mini-blocks, each containing one of two possible conditions: a resting (no-movement) and a movement condition. These conditions were presented in pairs of two consecutive mini-blocks, but the order of these conditions was randomized across both measurement days and participants. Each mini-block consisted of 48 trials. Within each mini-block, each of the six possible vibrotactile stimuli was presented six times, and each of the no-stimuli (catch) trials was presented twelve times (20% of all trials), all in a random order, at ~45 ms (range: 10-80 ms) after the trial onset. In the resting condition, the trial onset was defined by a key press on the left-hand keyboard while the right index finger rested on the button box. Conversely, in the movement condition, participants pressed and held down the button of the button box with their right index finger. Subsequently, they released the button and executed a comfortable extension

movement with their right index finger. In the moving condition, trial onset was marked by the release of the button, so the stimulus occurred always after movement onset. Participants indicated whether they detected a tactile stimulus at the end of each trial by pressing with their left hand one of two predefined keys on the keyboard. Each mini-block lasted ~6 minutes, with a 3-minute break between consecutive mini-blocks, resulting in a total duration of the experiment of ~50 minutes for each measurement session (day).

Data analysis

To examine possible changes in tactile perception and suppression within each measurement day, we first estimated detection thresholds for each participant, separately for each mini-block and movement condition (i.e., resting and moving). Specifically, we fitted the detection responses with a psychometric function using *psignifit 4* [29] in Matlab 2023b (The Mathworks Inc., Natick, Massachusetts). We did so separately for each of the six resting and moving mini-blocks within each day, obtaining six resting and six moving tactile detection thresholds per participant and measurement day. Because we presented the resting and moving mini-blocks in an alternating order, we quantified tactile suppression by subtracting the threshold from a given resting mini-block from the threshold of the corresponding moving mini-block. This resulted in six values (*Δthreshold*) per participant and measurement day that represent the effect of movement on tactile perception, with positive values indicating higher detection thresholds during movement than rest trials indicating higher movement-related tactile suppression.

We examined whether tactile perception and suppression were affected within and across measurement days. The statistical analyses were implemented in R Studio version 2023 4.2.3 [30]. For all analyses, we implemented linear mixed models (LMMs) using the *lmerTest* package in R [31]. The LMMs were fitted using the restricted maximum likelihood estimation. We initially checked model assumptions on a simple model consisting of fixed effects of movement, mini-block, day and random effect of participant with the *check_model* function. Visual inspection of model assumptions did not reveal any obvious deviations from normality of residuals, random effects, linear relationship, homogeneity of variance and multicollinearity. Two LMMs were conducted. The first LMM tested the effect of movement within and across measurement days on the detection thresholds and included the fixed effects terms movement, mini-block, day as well as their interactions. To account for other (known) sources of variability, the model included the following random effects: a random intercept for participants, which accounts for overall within-subject variability and a random slope for movement, which accounts for the variability across participants associated as a function of movement. The second LMM examined the tactile suppression effect, i.e., Δthresholds, within and across measurement days. In addition, as tactile suppression can be modulated by movement speed [32], we entered each participant's average movement speed in each condition as a covariate of no interest. This LMM included the fixed effects terms mini-block, measurement day and their interaction, average movement speed as covariate and the random effect term of participant. For all fixed effects of interest, we used dummy coding. We estimated the fixed effect terms with the *anova* function which performs an F-test on the fixed effects using the Satterthwaite approximation [33]. For post-hoc pairwise comparisons and estimated marginal means, we used the *emmeans* package [34].

For multiple pairwise comparisons, we used Bonferroni adjustment, when necessary. Effect sizes were calculated using the *effectsize* package in R as Cohen's *d* [35].

Any possible differences in tactile perception and suppression within and across measurement days would not directly address whether the magnitude of tactile suppression reported in the literature arises from temporal effects within and/or across measurement days. To address this, we quantified whether the observed differences between the earliest and latest mini-blocks within the measurement days were too small to be considered important. In detail, we first quantified the effect of movement on tactile perception based on the literature (i.e., effect size of movement-related tactile suppression), and then tested whether the observed differences between the earliest and latest mini-blocks as well as between the first and the last measurement days were within the margins of the effect size reported in the literature. To estimate the reported effect size, we reviewed the literature and found 41 studies on movement-related tactile suppression. Out of those, we considered 26 studies [8-10, 12, 14, 18-22, 36-50] that reported effect sizes in a direct (e.g., *Cohen's d*) or indirect manner (e.g., means, standard deviations and sample sizes). In case a study reported more than one related experiment, we used the smallest effect size across those experiments. We calculated the Cohen's *d* from those studies, which we weighted based on the corresponding sample size (i.e., [51]). This resulted in a true effect size of 1.28. We then used two independent one-sided t-tests to examine whether the observed differences in tactile perception and suppression between the first and last mini-blocks as well as between the first and last measurement days were within the margins of the true effect size (i.e. [-1.28 to 1.28]; equivalence testing; [52]). To this end, we first averaged the detection thresholds in each of the static and moving conditions, as well as the tactile suppression indices, across the earliest and latest mini-blocks of each measurement day, obtaining an *early* and a *late* detection threshold for each of the resting and moving conditions, as well as an *early* and a *late* tactile suppression index. We also examined whether the observed differences in tactile perception and suppression between the first and last measurement days were within the margins of the true effect size. To this end, we fitted new psychometric functions for each measurement day, separately for each (resting and moving) condition and per participant, by merging the responses across all mini-blocks of the respective condition and the respective day. This can result in more reliable fits while still allowing us to obtain detection thresholds for the resting and moving conditions, as well as the resulting tactile suppression indices. The equivalence tests were conducted in Jamovi 2.5.4 [53] using the TOSTER package.

Results

We first tested how tactile detection performance changes as a function of movement within and across days. The results can be found in Table 1.

Table 1. *Fixed effects of interest from the LMM on detection threshold obtained in the resting and moving conditions. Statistics are reported for each item with sum of squares (SS), mean squares (MS), degrees of freedom (dfs), F-value (F) and p-value (p).*

	SS	***MS***	***dfs***	***F***	***p***
Movement	5.93	5.93	1, 23	14.70	< 0.001
Mini-block	20.30	4.06	5, 1058	10.07	< 0.001
Day	9.15	3.05	3, 1058	7.57	< 0.001
Movement * mini-block	8.11	1.62	5, 1058	4.02	0.001
Movement * day	6.58	2.19	3, 1058	5.44	0.001
Mini-block * day	3.88	0.26	15, 1058	0.64	0.84
Movement * mini-block * day	2.72	0.18	15, 1058	0.45	0.96

As expected, detection thresholds were higher during movement than resting conditions, indicating tactile suppression. Main effects of mini-blocks and measurement days were also significant but because these effects depended on the movement condition we will focus on the respective interactions. Planned post-hoc comparisons exploring the movement by mini-block interaction revealed that detection thresholds during the moving condition were lower in mini-block 1 relative to mini-blocks 4, 5, and 6 (all estimates > 0.44, all t > 4.84, all *d* > 0.30, all p < 0.001), as well as in mini-blocks 2 and 3 relative to mini-block 6 (both estimates > 0.43, both t > 4.68, both *d* > 0.29, both p < 0.001). No differences between mini-blocks were found in the resting condition. These results suggest poorer perception with more exposure to the mini-blocks but only in trials involving movement. Planned post-hoc comparisons exploring the movement by measurement day interaction revealed lower detection thresholds in the moving condition in day 2 relative to days 3 and 4 (both estimates > 0.37, both t > 4.92, both *d* > 0.30, both p < 0.001). Again, no differences across days were found in the resting condition. Together, the results demonstrated that detection thresholds can change both within and across days but only when the stimulated limb is moving.

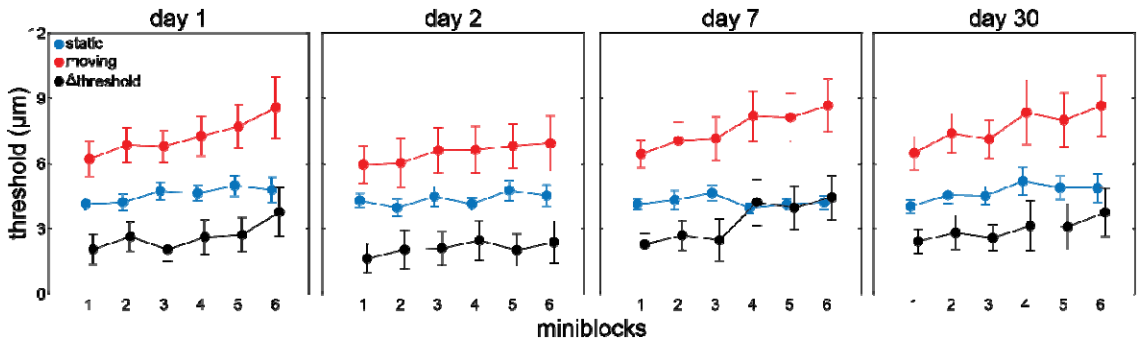

Figure 2. Tactile perception within each measurement day. *Tactile detection thresholds during resting (blue) and moving (red) trials, as well as their relative difference (suppression; black), separately per mini-block and day. Symbols represent averages across participants with error bars denoting the standard error of the mean.*

The second LMM focused on the tactile suppression effect (Δthresholds) and tested if tactile suppression changes within and across measurement days while accounting for movement speed, because movement speed may modulate tactile suppression (e.g., 33; but see also [50, 54]). There were main effects of mini-block and measurement day on Δthresholds (see Table 2). Post-hoc pairwise comparisons on the effect of mini-block revealed significantly lower Δthresholds in mini-blocks 1 and 3 relative to mini-block 6 (both estimates > 0.43, both t > 3.63, both *d* > 0.32, both p <= 0.003). Likewise, post-hoc pairwise comparisons on the effect of day revealed significantly lower Δthresholds in day 2 relative to days 3 and 4 (both estimates > 0.28, both t > 2.95, both *d* > 0.26, both p <= 0.02). These results indicate that tactile suppression can increase within short and longer time periods after controlling for movement speed.

Table 2. *Fixed effects of interest from the LMM on Δthreshold. Details as in Table 1.*

	SS	***MS***	***dfs***	***F***	***p***
Mini-block	16.20	3.24	5, 528.01	4.88	< 0.001
Day	13.16	4.39	3, 528.20	6.61	< 0.001
Mini-block * day	5.43	0.36	15, 528.01	0.55	0.92
Movement speed	0.03	0.03	1, 540.68	0.04	0.84

These results demonstrate that tactile perception during movement can deteriorate over time. Does this mean that such changes can explain the tactile suppression phenomenon reported in the literature? To address this, we examined whether the observed effect between the first and the last mini-blocks as well as between the first and last measurement day was smaller than the effect size as we calculated it based on the literature (see Methods). The two one-sided t-tests of the equivalence testing procedure applied separately to the resting and moving thresholds, as well as to the *Δthresholds*, reveal that the observed differences between the first and last mini-blocks within measurement days were negligible to explain the phenomenon of tactile suppression. Indeed, the observed effect sizes were within the margins of the true effect size for the resting detection thresholds (both $|t|$ >

4.85, both $p < 0.001$), the moving detection thresholds (both $|t| > 4.15$, both $p < 0.001$), and the *Δthresholds* (both $|t| > 4.37$, both $p < 0.001$). Likewise, the differences between the first and the last measurement days is smaller than the difference expected from the results reported in the literature. Specifically, the observed effect sizes of the differences between the first and last measurement day were within the margins of the true effect size for the resting detection thresholds (both $|t| > 5.54$, both $p < 0.001$), the moving detection thresholds (both $|t| > 4.99$, both $p < 0.001$), and the *Δthresholds* (both $|t| > 5.41$, both $p < 0.001$). We can thus reject the hypothesis that the observed differences within and across days are at least as extreme as the higher and lower margins of the true effect size, and can conclude that possible differences in tactile perception and suppression within and across measurement days can be considered negligible with respect to the observed tactile suppression phenomenon described in the literature. In other words, the effects observed within and across measurement days are unlikely to drive the tactile suppression effects reported in the literature.

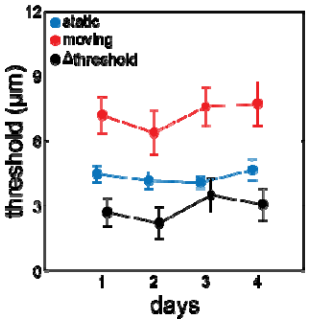

Figure 3. Tactile perception across measurement days. *Tactile detection thresholds during rest (blue) and movement (red) trials, as well as their relative difference (suppression; black), for each measurement day. Symbols represent averages across participants with error bars denoting the standard error of the mean.*

Discussion

In this study, we examined whether tactile perception on a resting and a moving limb, as well as movement-related tactile suppression change with exposure to a tactile task. Participants had to detect probing tactile stimuli on their right index finger, while this finger was resting or moving. These detection tasks were repeated across four separate sessions within a period of 30 days. Our results demonstrate that tactile perception during rest is robust within single measurement sessions, at least within the 60-minutes time window during which we assessed tactile performance. Likewise, we show generally robust tactile perception during rest across measurement days. In contrast, we observed poorer tactile perception during movement with more exposure to the task both within and across measurement days. Importantly, though, this effect cannot explain the well-established phenomenon of tactile suppression, as the differences within and across measurement days were overall smaller than the tactile suppression effects reported in the literature.

Tactile detection thresholds on a resting limb were highly robust both within and across measurement days. One might have expected improved detection with longer exposure to the experimental task and tactile stimulation, perhaps due to increased familiarity with the task and stimuli. Several studies have shown that repeated exposure to a task can cause a learning cascade of perceptual skills [23, 55, 56]. Despite this, we have no evidence that tactile perception during rest improves with more exposure to the task and the chosen tactile stimuli. This might arise due to the already high sensitivity of our participants during resting trials, during which they felt the weakest possible stimulus, making it impossible to observe any possible improvement over time. Such a ceiling effect, in which the weakest tactile stimulus is already detectable may not allow for improvement in performance. One might have also expected that systematic stimulation of the tactile receptors on the index finger could lead the stimulated receptors to adapt, with the consequence of observing poorer sensitivity over time [24, 25]. Our data lend no evidence for this either. The mechanoreceptor properties that encode discriminative aspects of vibratory stimuli may make such adaptation unlikely as high frequency vibrations activate fast-adapting mechanoreceptors that adapt quickly in response to stimuli, primarily those moving across the skin [57, 58]. It can be argued that the fast-adapting properties of activated units contributed to the lack of adaptation in the rest condition. The robustness of

resting tactile detection thresholds within and across measurement days demonstrates that the exposure to tactile stimuli does not have any worthwhile impact on how well our participants detected those stimuli.

Tactile detection thresholds on a finger that was moving were higher with more exposure to the task. Detection thresholds during movement increased within measurement days reflecting poorer sensitivity with more exposure to the task, at least within the ~60 minutes (duration of one measurement session). In addition, detection thresholds during movement were higher in the third (day 7) and fourth (day 30) relative to the second measurement day (day 2). This suggests that detection thresholds during movement increase with more exposure to the task. However, if the increased thresholds were simply due to more exposure to the task, one might have expected the lowest detection thresholds to occur on the first measurement day. Yet, there was no difference between the first and any other measurement day. As can be seen in Figure 3, detection thresholds during movement are somewhat lower on day 2 than day 1. This apparent relative improvement in tactile sensitivity on day 2, though not statistically significant, might drive the effect of poorer sensitivity on days 7 and 30. It is likely that differences in the time interval across the measurement days may have influenced detection performance during movement. Although our task did not require participants to become more accurate in detection, some form of sensorimotor learning might have taken place in the initial two days, but failed to last for long, as has been shown for motor skill learning [59]. Whatever the reason for this modulation of the detection thresholds in the moving condition, it is important to note that the differences between the first and last mini-blocks, as well as between the first and last measurement days were so small that they cannot explain the movement-related tactile suppression effects reported in the literature.

Tactile suppression was evident in all mini-blocks and measurement sessions, in line with an abundance of studies showing poorer sensitivity to tactile stimuli presented around movement compared to rest [7, 11, 17]. The strength of suppression was somewhat variable within measurement days as it was larger in the last mini-block compared to the first and third. Although this reflects increased suppression with more exposure to the task within a single measurement session, it should be interpreted with caution because we did not find any other systematic differences within single measurement days. Likewise, although we found that tactile suppression changes across days, this change is neither linear nor

367 systematic. Indeed, suppression is stronger in measurement days 3 and 4 (days 7 and 30)
368 relative to day 2, but not relative to day 1. Therefore, although exposure to the tactile task
369 could lead to increased tactile suppression, it is not enough to explain the observed pattern
370 of results.

371 Why were detection thresholds during the moving condition, as well as tactile
372 suppression, higher on measurement days 3 and 4 relative to measurement day 2? This
373 effect might in fact arise from improved sensitivity (i.e., lower thresholds) during session 2,
374 perhaps because this session took place on the day immediately after the measurement day
375 1. This close temporal proximity might have helped in performing the detection task.
376 However, if this would be the case, one might have also expected improved perception
377 either also within measurement days or between measurement days 1 and 2 during resting
378 trials. Since we found differences within and across days only when moving, kinematic
379 factors might have influenced the related results. For instance, higher movement speeds can
380 influence the magnitude of tactile suppression [32, 50]. For this reason, we included
381 movement speed as a covariate in our analyses to account for the potential influence of
382 change in movement speed as a function of time. Another factor that could influence tactile
383 perception is the time of stimulus presentation relative to movement onset [7, 60].
384 However, our stimuli were presented always between 10 and 80 ms (on average at 45 ms)
385 after the onset of the movement, so this factor cannot have influenced our results
386 Therefore, the reasons for the tactile modulation on sessions 3 and 4 relative to session 2
387 are still open for further investigations.

388 Our results have implications for wearables and for haptic technologies designed to
389 foster human-machine interactions, such as devices that provide tactile signals with
390 informational value to actors, e.g., telesurgeons or humans acting within virtual or remote
391 settings. It is important to keep in mind that the informational value and fidelity of such
392 tactile signals can drastically change once these are presented on a moving than resting limb
393 and that the perception of such signals can change over time. There is therefore a need for
394 more research on the effects of tactile information on a moving body during movement and
395 over time, and how this may depend on the complexity of the performed task and of
396 inherent individual differences that may, for instance, depend on age or other cognitive or
397 physiological properties.

We conclude that tactile perception during resting is robust both within and across days. However, tactile perception during movement and tactile suppression may change to some extent within and across measurement sessions, though these changes are neither systematic nor linear. Importantly, any possible differences in tactile perception and suppression over time cannot explain the movement-related tactile suppression effects reported in the literature.

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