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Research Article

Modulation of sensory attenuation by intensive meditation practice: an active inference perspective

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Abstract

Active inference describes motor action as a prediction-driven inferential process, whereby ascending proprioceptive prediction errors are attenuated to allow the fulfillment of expected movement. Meditative practices typically involve a heightened attention to bodily sensations, begging the question of whether this could partially offset the normal proprioceptive suppression during a simple motor act. In this study, 42 experienced meditators completed a tactile force-matching task, designed to measure somatosensory attenuation. The active group ($N = 19$) performed the task before (T1), during (T2), and three weeks after (T3) an intensive 10-day mindfulness meditation retreat, while a control waiting list group ($N = 23$) was also measured three times, but before participating in the retreat. Analysis of T1 data confirmed the presence of a general somatosensory attenuation effect across groups, which correlated negatively with pre-retreat trait measures of mindfulness, as predicted by our hypothesis. Contrary to our expectations, however, longitudinal analyses did not reveal a global reduction in somatosensory attenuation as an effect of intensive meditation practice. We observed instead a subtler regression-to-the-mean effect at T1, which increased with task repetition in control participants (T1>T2>T3), a training-related phenomenon not previously reported for the force-matching task. Interestingly, this habituation behavior was not shown by the active participants, who maintained the level of regression-to-the-mean observed at baseline at T2, suggesting that the formation of prior expectations about the presented force intensity may be affected by the retreat. We discuss how multiple, opposite effects of meditation on proprioceptive active inference mechanisms, and/or an alteration of prior formation and their influence, may explain these findings.

Keywords: force-matching; sensory attenuation; active inference; mindfulness; meditation retreat

Introduction

Navigating through a diverse and ever-changing environment demands constant adaptation from both our brain and body. Activities like climbing a steep mountain or crossing a tumultuous river require different motor behaviors from walking upon a flat grassland. In this dynamical context, evaluating the consequences of our own movement is crucial for a real-time tuning of our actions (Waszak et al., 2012). Classic motor control theories propose that when executing a voluntary movement, an efference copy of the motor command would also be produced to predict its most likely sensory consequences (Blakemore et al., 1998, Wolpert and Flanagan, 2001). Such sensory predictions would then be used to discriminate motion-induced sensations—which are expected and consequently attenuated—from unpredicted external sensations, the most relevant in terms of useful information. The resulting attenuation of the sensory consequences of one's own movement is referred to as "sensory attenuation" (Blakemore et al., 2000). A simple illustration of sensory attenuation is provided by trying to tickle oneself. The irresistible tickling sensations typically experienced when the action is performed by someone else, and thus not easily predictable, quickly vanish when we voluntarily initiate the same action ourselves and are thus able to predict them precisely (Blakemore et al., 2000). Also, sensory attenuation extends beyond tactile sensations and encompasses the realms of both visual and auditory experiences (Hughes and Waszak, 2011, Horváth, 2015).

Active inference is a recent theoretical approach that, starting from first principles, aims to describe under the same Bayesian mechanistic framework the various cognitive and behavioral features of sentient systems, such as perception, action, attention, learning, and planning (Parr et al., 2022). From the perspective of active inference, a bodily movement is initiated by a prediction of the sequence of sensory (especially proprioceptive) consequences of the intended motor act—in fact, a conceptual reframing of the efference copy mechanism—which is then fulfilled by spinal reflex loops. In order for this to occur, however, the actual proprioceptive signals must be attenuated during the unfolding of the action, to prevent them from falsifying the original prediction of movement and thus stopping the nascent motor act at its inception (Brown et al., 2013). In other words, initiating a movement

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requires the effective suppression of sensory input that registers the body as stationary.

Tactile sensory attenuation has been tested extensively with the force-matching paradigm (Shergill et al., 2003), where a force is first applied via a lever on the "receiving" finger (e.g. left index) of the participant by a torque motor, and she is then asked to replicate the perceived force intensity in different conditions. In the condition of interest (often labeled "Direct"), they press on their receiving finger with a finger from the other hand (e.g. right index). In contrast, in a control condition, participants indirectly reproduce the target force by operating the motor lever through an external device (often a slider) located at a distance from the receiving finger, an action whose sensory consequences are typically less predictable, barring a specific training with the device (Blakemore et al., 1998). Typically, in the "Direct contact" condition—but not in the control one—participants tend to produce a greater force than the one they are trying to match, which has been interpreted as signaling an attenuation of the predicted sensations generated by one's own actions (Shergill et al., 2003, Bays et al., 2006, 2008, Shergill et al., 2013). Sensory attenuation seems in fact to be reduced not only by the indirectness of the application of the reproduced force (as when using a slider in the control condition), but also by experimentally introducing temporal delays (Bays et al., 2005) or spatial misalignment (Bays et al., 2008, Kilteni and Ehrsson, 2017), disrupting the natural predictability of the sensory consequences of a movement.

Somatosensory attenuation is a ubiquitous phenomenon observed in the vast majority of healthy adults. In the largest study to date with the force-matching paradigm (Wolpe et al., 2016), 98% of 322 participants (aged between 18 and 88 years old) showed the effect. Interestingly, in that study, force overcompensation was found to be enhanced by aging in the "Direct" condition, but decreased by it in the "Slider" condition. The authors argued that this increase in somatosensory attenuation with aging may be due to an age-related shift in precision weighting balance, with reduced precision of sensations and increased precision of sensory predictions (Wolpe et al., 2016). Conversely, it has been suggested that a failure to attenuate the somatosensory consequences of movements in patients with schizophrenia (Shergill et al., 2005, 2014) or functional movement disorders (Pareés et al., 2014), is at the basis of false inferences about agency in these clinical populations (Brown et al., 2013). In healthy subjects, psychometric scores of delusional ideation (Teufel et al., 2010), as well as the positive dimension of schizotypy (Asimakidou et al., 2022), have also been related to a reduction of sensory attenuation.

The aim of the present study was to test the effect of meditative practice on the performance of the force-matching task. This was predicated on the fact that meditation typically involves a heightened awareness of bodily sensations, even when intentionally performing an action, which could be seen as setting a high precision on the somatosensory signals. We thus hypothesized that individuals with a long history of meditative practice would be paying a greater attention to the sensations from their receiving finger during the force-matching task, thereby partially offsetting the natural somatosensory attenuation. Coherently with this hypothesis, there is some evidence in the literature for a higher sensory accuracy in meditation practitioners (Fox et al., 2012, Mirams et al., 2013). We expected this effect to be enhanced during an intensive 10-day meditation retreat and measurable through the force-matching paradigm as a decrease of sensory attenuation.

Furthermore, the recruitment of a sample of meditation practitioners with various degrees of experience allowed us to investigate the trait effect of long-term meditative practice by testing the relationship between somatosensory attenuation and self-reported measures of interoception and mindfulness that are thought to be trained in meditation (Farb et al., 2015, Gibson, 2019). Interoception is defined not only by the "sensory awareness that originates from within the body's physiological state" but also by one's "appraisal, attitude, beliefs, past experiences and expectations" toward this perceptual experience (Gibson, 2019). In the context of mind-body therapies, a trait measure of interoception is commonly obtained through the Multidimensional Assessment of Interoceptive Awareness (MAIA, Mehling et al. (2012)), which aims to capture the inherent multidimensional nature of body awareness. Mindfulness, on the other hand, is a complex construct surrounded by semantic ambiguity and nowadays applied very broadly (Lutz et al., 2015, Van Dam et al., 2018). One way to measure it as a psychological trait is through the Five Facet Mindfulness Questionnaire (FFMQ), which decomposes the overall construct of mindfulness in five factors: observing, describing, acting with awareness, non-judging of inner experience, and non-reactivity to inner experience. Interoception and mindfulness have been shown to be related, yet distinct, constructs (Hanley et al., 2017), both involving a specific stance toward body sensations and movements. In particular, the progressive development of perceptual sensitivity and accuracy through mind-body practices training (Kerr et al., 2008, Fox et al., 2012, Mirams et al., 2013) may globally increase the precision of sensory inputs and consequently diminish the sensory attenuation phenomenon.

We expected, therefore, to observe negative correlations between our participants' degree of sensory attenuation, on one side, and self-reported FFMQ/MAIA sub-dimensions related to perception and action—as well as their lifetime meditation experience—on the other. Finally, we evaluated multiple phenomenological dimensions associated with the experience of performing the force-matching task, such as the saliency of sensations, attention to fingertips, confidence in force estimation, awareness of movements and physical tension. Given the rich dynamics observed across multiple dimensions of lived experience during the meditation retreat in the same study (Abdoun et al., 2025), we also expected to observe changes in the phenomenological dimensions just mentioned, as well as potential correlations with the level of sensory attenuation of our participants.

Materials and methods

Ethics statement and participants

The experiment and analyses described hereafter are part of a broader study of the longitudinal effects of mindfulness meditation practice during an intensive retreat titled "LONGIMED," which received approval from an independent ethics committee on human research (CPP Est IV 2020-A00669-30, ClinicalTrials.gov Identifier: NCT04449913). Forty-two healthy adults with ongoing meditation experience in mindfulness-related practices took part in the force-matching experiment. Important inclusion criteria were: age between 18 and 67, speaking French fluently, having been trained in a formal meditation practice (mindfulness, MBSR, Buddhist traditions, etc), having a regular practice of at least 20 min per day three times a week for at least one year, and having already participated in a silent meditation retreat of at least two days with a minimum of 6 h of meditation per day. Exclusion criteria of interest to the current report were: any neurological or psychiatric history, sensory or motor deficiencies of the hands, or regularly taking medications with effects on the central nervous system.

Study design

All participants in this experiment joined one of the two 10-day mindfulness meditation retreats we organized in January and March 2021 in southern Jura (France). Both retreats were supervised by Stephane Offort, a qualified Mindfulness-Based Stress Reduction program (MBSR) instructor, who is also extensively trained in the Karma-Kagyu tradition of Tibetan Buddhism (traditional 3-year retreat and 12 years of solitary retreat). The instructor delivered a fully secular meditation training in which the instructions followed the typical program of mindfulness-based interventions. The retreats took place in silence, with communication restricted to the bare minimum; participants were also encouraged not to use electronic devices, especially smartphones. The daily schedule included ∼7 h of formal group meditation split into eight sessions of 45–60 min.

For this paradigm, participants were randomly assigned to an "active" or to a waiting-list "control" group (age- and gender-matched), before starting the study (active subjects: $n = 19$, 11 females, mean age ± st.dev. = 46 ± 12 years, average meditation experience ± st.dev. = 1613 ± 2005 h; Control subjects: $n = 23$, 11 females, mean age = 45 ± 11 years, average meditation experience = 1873 ± 2578 h). A graphical representation of the study timeline is visible in Fig. 1a. Active participants were first tested on-site upon their arrival at the retreat center, one or two days before the beginning of the retreat (baseline measure, "T1"), then 7 days later at days 6 or 7 of the retreat (retreat measure, "T2") depending on the date of their first measure, and a last time at a minimum of three weeks after their second measure (follow-up measure, "T3," between 21 and 30 days from T2, except for one participant who could only be assayed 40 days after the end of the retreat, due to medical issues). This last measurement (T3) was collected at the laboratory. To control for a potential habituation to our experimental task that would explain a difference in results at T2, we also tested control subjects three times with the same delay between measures as the active group (7 days between T1 and T2 and 21–30 days between T2 and T3), but in the laboratory and before their participation to the retreat. Importantly, control participants were recruited with the same criteria as the active ones, and participated to the same pre/post brain imaging measurements (paradigm not presented here), as well as in-retreat phenomenological measures (Abdoun et al., 2025). This design allowed us to increase our sample size for some measures while ensuring similar motivational levels in both groups (group attribution was simply indicated as group 1 or group 2 to participants).

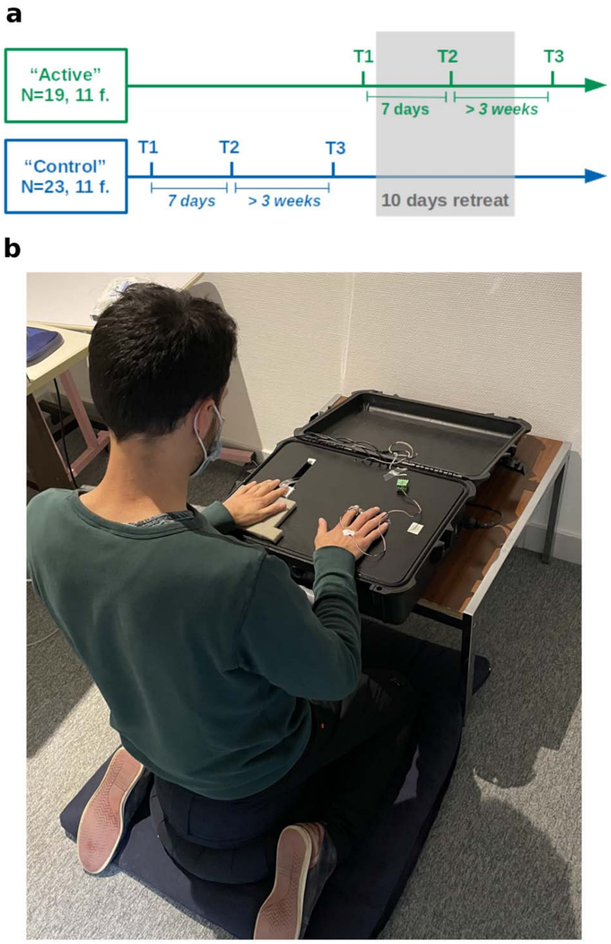


Figure 1. Study design and experimental setup. (a) A total of 42 participants were recruited through strict inclusion and exclusion criteria (see main text) and randomized into two experimental arms: "active" and waiting-list "control." Both groups participated to a 10-day meditation retreat, with participants into the active group being measured before (T1), during (T2) and after (T3) the retreat; while participants belonging to the control group were also measured 3 times, with the same timeline, but before their participation to the retreat. N: Total number of participants in each group, f.: number of female participants. (b) A transportable force-matching device was created to allow participants to seat in a meditation posture while doing the task in the laboratory or at the meditation retreat center. Participants were instructed to perform the task with a meditative stance, maintaining awareness on their sensations and movements.

Psychometric questionnaires and meditation experience

Two questionnaires filled out by participants in the LONGIMED study concern us here: the MAIA and the Five Facets Mindfulness Questionnaire (FFMQ). The MAIA is a 32-item validated questionnaire measuring various dimensions of interoceptive body awareness through 6-point Likert scales (Mehling et al., 2012): "Noticing," "Not distracting," "Not worrying," "Attentional regulation," "Emotional awareness," "Self regulation," "Body listening," "Trusting sensations." We used an unofficial French translation of the questionnaire, as no validated version was available at the time of the study design. The version we used turned out to be very similar to a validated one published later (Willem et al., 2021). The FFMQ is a 39-item validated questionnaire targeting different aspects of trait mindfulness and composed of five main facets: "Observing," "Describing," "Acting with awareness," "Non-judging" and "Non-reacting" (Baer et al., 2006). We used a validated French translation of the 5-point Likert scales (Heeren et al., 2011). Our hypothesis was that the dimensions of these two questionnaires that relate to sensory and bodily signals, and to attention (MAIA: "Noticing," "Not distracting," "Attentional regulation," "Body listening," "Trusting sensations;" FFMQ: "Observe" and "Act with awareness") would be more correlated to sensory attenuation (negatively or positively depending on the dimension) than other dimensions targetting emotional or thought processes. We also aimed at quantifying participants' meditation experience through a personal interview, estimating their total time of practice since they started meditating ("Lifetime practice," hours), their current daily practice duration ("Daily practice," minutes), and an estimation of the overall time spent in meditation retreats up to their enrollment in the study ("Retreat practice," hours). Under our main hypothesis of meditation practice decreasing sensory attenuation, we expected these measures to correlate negatively with sensory attenuation.

Experimental paradigm

Materials

We used a custom, portable setup, visible in Fig. 1b, to conduct the force-matching task in both the laboratory and a meditation retreat environment. Participants sat in a comfortable meditation posture with their left hand resting on a support at elbow height and their right hand 15 cm apart and equipped with a ring force sensor ("TouchyFinger" prototype, École Centrale de Lyon - Laboratoire de Tribologie et Dynamique des Systèmes). The left index finger was positioned with the fleshy part of the fingertip (finger pad) facing down, under a lever controlled by an electric motor (Maxon EC 90) whose functioning was hidden from the participants. The force sensor, positioned on the nail side of the right index finger, was a prototype version of the TouchyFinger device. It consisted of a semi-flexible plastic ring adjusted on the participant's fingertip and equipped with a deformation sensor. Any pressure applied by the finger pad leads to the deformation of the finger skin and, therefore, to the extension of the ring measured by the sensor. The TouchyFinger was sensitive enough to detect changes in finger pad deformation caused by the cardiac cycle and allowed us to measure force applications without any sensor device between the fingers. Three ring sizes were used to adapt to various finger sizes and could be adjusted if necessary. The ring sensor was calibrated multiple times throughout the experiment using a force scale situated below the left finger. Force applications, ring sensory measurements and timings of the experiment were automatized through custom scripts in Labview.

Trial sequence and force-matching conditions

We investigated three different conditions of force reproduction. Each trial always started with an auditory tone, followed 500 ms later by the application of the target force on the tip of the left finger (nail side) via the lever. Force was applied with an initial 500 ms ramping up phase, followed by a 3 s plateau at the target force level, and ending with a 500 ms phase that brought the force back to zero. A different auditory tone signaled to the participant the end of the presentation phase and the beginning of the force reproduction phase of the trial, whose modality varied between conditions, as shown in Fig. 2. Our first condition is the most similar to the "direct" condition commonly used in force-matching paradigms (Kilteni and Ehrsson, 2017, McNaughton et al., 2021): the lever remained above the left index finger after the target force presentation, and participants had to place their right finger on top of the lever and press downward on it to reproduce the force previously experienced on the left finger. To distinguish this experimental condition from the next one described below, we will refer to it as the "mediated contact" condition, indicating the intermediate presence of the lever between the acting and the sensing finger.

In a second experimental condition, after force presentation, the lever was automatically lifted up and participants had to place their right index finger directly on top of the left one and press downward on it to, once again, reproduce as best as possible the target force intensity. This was our main condition of interest, replicating what was previously done in the literature with a small but important difference: the use of the TouchyFinger device allowed us to test a *true* direct contact between the acting and the sensing fingers, the force sensor being located on top (nail) and on the side of the acting finger (as displayed in Fig. 2), letting the pad of the skin bare. Indeed, all previous studies used a force measuring sensor placed over the pad of one of the fingers or onto the lever for practical reasons (Kilteni and Holmes, 2023), bypassing the directness experienced in a natural contact setting. This condition was therefore named "direct contact" condition. We were interested to determine whether the more realistic contact condition enabled by the TouchyFinger would influence the somatosensory attenuation phenomenon.

Finally, in the last condition, the lever also remained in place and participants had to place their right index finger on the white patch located 25 cm to the right of the left finger, as shown in Fig. 2. From this position they had to reproduce the target force indirectly, by controlling the motor by exerting pressure with the finger on the white patch. The force measured by the ring sensor was transmitted with virtually no delay to the motor, which caused the lever to press on the left index finger, as in the presentation phase. In this case too, our control condition, which we will refer to as the "remote" condition because of the distance between the force-delivering and the force-receiving finger, was a variation of the control condition (as in Kilteni and Ehrsson (2017)) used in the classical force-matching task, which involves the use of a slider to deliver the intended force level. This choice has the advantage of keeping the same downward pressure movement as in the conditions of interest (instead of a sliding movement in the slider condition), while disrupting the sensory attenuation phenomenon if the pressure is exerted far enough from the left finger (Bays et al., 2008, Kilteni and Ehrsson, 2017).

Independently of the condition, participants were instructed to maintain the target force for about 3 s; however, no strict duration was imposed and precision was favored over speed. The trial ended when they returned their right finger to the resting position, where a sensor detected it, and the end of the trial was signaled by an auditory tone. Importantly, participants sat in a meditation posture and received instructions to perform the task as well as they could, while maintaining awareness of their sensations and movements.

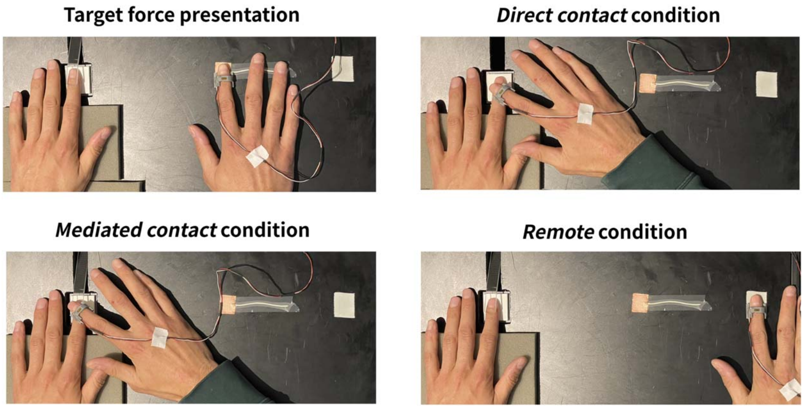
Factorial design

Participants underwent five repetitions of six different target forces (1, 1.5, 2, 2.5, 3, 3.5 N) in each condition. Two blocks of fifteen consecutive trials were separated by a pause during which the experimenter asked the participants detailed questions about their physical and mental experiences during the task (phenomenological scales, detailed in the next section). All the trials for the same condition were presented in a row, with pseudo-randomization of the different target forces. At the beginning of a new condition, the ring sensor was calibrated again and five training trials were presented, with explanations and potential corrections by the experimenter. The order of the conditions was pseudo-randomized across participants.

Phenomenological scales

In order to assess the mental and physical dimensions of conscious experience in relation to meditation during the task, we prompted participants with five phenomenological questions after every block of 15 trials. All questions were asked orally by the experimenter and answered by the participants on a 0 to 10 Likert-like scale:

- **Saliency** "How salient were the sensations on the index fingers? From 0 not salient to 10 very salient." Without distinction between left and right fingers.



Target force presentation

Direct contact **condition**

Mediated contact **condition**

Remote **condition**

Figure 2. Illustration of the different force-matching conditions. The presentation of the target force to match is done in "resting" position, the left index finger is positioned under the motored lever and the right index finger, with the ring sensor attached, is at rest on a detection sensor 15 cm apart. In the "direct contact" condition, participants reproduced the target force by pressing directly on the left index fingertip (nail side) with their right index finger pad. After matching the force in intensity for about 3s, participants went back to resting position for a new trial to start. In the "mediated contact" condition, the right finger had to reproduce the same force on the left index finger by pressing on the lever with the right one. Finally, in the "remote" condition, participants matched the force by pressing on the white patch 25 cm apart from the left finger, and the applied force was directly transmitted to the left index fingertip through the motored lever.

- **Confidence** "To what extent did you feel doubt or confidence in your estimation of the target force? 0 high doubt, 5 neither doubt nor confidence, 10 high confidence."
- **Attention** "To what extent was your attention directed toward your index fingers? 0 not at all, 10 fully."
- **Movement** "How much were you immobile in your meditation posture? 0 perfectly immobile to 10 many postural movements." Finger and arm movements which were part of the task were not included in this estimation.
- **Physical tension** "To what degree were you relaxed physically? 0 very relaxed, 10 very tense, agitated.

Data processing

All force pressure signals were downsampled to a 10 ms temporal grid, which gives sufficient accuracy for the effect studied here. We excluded trials shorter than 2 s and longer than 20 s or with an amplitude smaller than 0.25 N and larger than 40 N (2% rejection rate). To remove inessential high-frequency components from the force measurements, the data were smoothed with a 50 ms window. Several window sizes were compared to find the most appropriate one (20, 30, 50, 80 ms). The "matching force" for a given trial was calculated as the average of the force measured by the ring sensor between 1 and 0.5 s before the participant lifted her right index finger and corrected by a "baseline force," defined as the average force between 250 and 500 ms after finger lifting. We chose this time window as a baseline as it provided a more stable measure than the force applied at the beginning of the trial, which exhibited a progressive ramping up. The specific "release time" for the onset of the baseline period was calculated as the time at which the force derivative (speed) was negatively maximal, and was constrained to occur in the second half of the trial and before the last 100 ms to avoid artifacts that could arise at the beginning of the next trial. The "matching force" period of interest was chosen as the interval from 1 to 0.5 s before the release time, since participants were instructed to maintain a stable force for at least 3 s. The baseline period allowed us to correct for a potential ring sensor offset as the finger was being put back into the starting position and so no force was applied during this time. The release time was chosen as the reference time for the definition of both the matched force and the baseline force periods, because it was more easily and unambiguously identifiable compared to the onset of pressure delivery. Sensory attenuation was defined in each trial as the difference in Newtons between the force applied by the participant (matched force) and the force they were instructed to match (target force). All processing steps were performed on Python3 (Van Rossum and Drake, 2009).

After data processing, one subject appeared to be a clear outlier with an average sensory attenuation in the direct contact condition five standard deviation higher than the participants group average, and was thus excluded from further analyses related to force signals—but kept in the analyses of the phenomenological questions. In addition, due to software issues during recording, six participants had incomplete data for the direct contact condition at T1 (four for the mediated condition, two for remote), one participant for the direct condition at T2 (two for the mediated), and one for mediated at T3 (two for remote). Finally, four participants did not show up for the follow-up measurement (T3). As we used linear mixed models or Bayesian regression models that can accommodate missing or incomplete data, this did not impact our analyses of force measures. Yet, this became problematic for correlation analyses where data were averaged over trials for each subject, and we thus decided to remove participants with incomplete data in this case.

Statistical modeling of baseline (T1) data - Bayesian model

We used a hierarchical (or multilevel) Bayesian regression model to assess the effects of "target" force, and "condition" on "matched force" at the baseline measure (T1), where subjects from both groups were pooled together for the analysis of the data collected before any meditation intervention. Target force was treated as a continuous regressor with values from 1 to 3.5 N, while condition was treated as a categorical regressor with three levels (*direct contact*, *mediated contact*, and *remote*). Varying (or random) intercepts were modeled per subject, as well as varying slopes per target force and for the three levels of condition, respectively, for each subject, giving the following formula in classical modeling notation:

$$\begin{aligned} &\textit{Matched force} \sim \textit{Condition} \times \textit{Target force} \\ &+ (1 + \textit{Condition} + \textit{Target force} \mid \textit{Subject}) \end{aligned} \tag{1}$$

A hierarchical modeling structure performs partial pooling, or shrinkage, of varying cluster-level estimates (random effects per subject), toward a fixed population-level mean, and allows therefore to explain general patterns of the data while taking into account inter-individual variability (Gelman and Hill, 2006).

Priors

We defined informative priors for our models' parameters using domain knowledge from the literature on force-matching (Walsh et al., 2011, Wolpe et al., 2016, Kilteni and Ehrsson, 2017). The prior for the global intercept was defined as a normal distribution with mean 1 and standard deviation 2. All other priors were normally distributed and centered on 0, with a standard deviation of 3 for population-level regression coefficients, and 2 for cluster-level (random) intercepts and slopes (see Supplementary Table S1). As we had two cluster-level effects, their correlation also had to be estimated, we used a LKJ-correlation prior with parameter $\zeta = 0.5$ (Bürkner, 2017).

Modeling and diagnostics

To fit Bayesian models we used the *brms* package (Bürkner, 2017) on R (R Core Team, 2018), which uses Stan's Hamiltonian Monte Carlo sampler algorithm to approximate the posterior distribution (Hoffman and Gelman, 2014, S. D. Team). We ran 4 Monte Carlo Markov Chain (MCMC) chains with 12 000 iterations each (including 2000 warm-up iterations), totaling 40 000 posterior samples, an appropriate number for robust Bayes Factor (BF) estimation. Model diagnostics were systematically checked ($\hat{R}$ and effective sample size) and we additionally performed posterior predictive checks to get a sense of the absolute goodness of fit of our winning model (Schad et al., 2021). The goal of this procedure is to examine whether a model accurately captured some key features of the data, by simulating posterior predictions for different summary statistics (e.g. mean and standard deviation), and observing where the real data point statistics fall within these posterior distributions.

Testing the interaction

In order to assess the evidence in favor of the interaction term in our model, as well as cluster-level (or random) effects, we ran similar models without the effects of interest and compared them with BFs. BF in favor of the full model were computed as the difference in log marginal likelihood between this model and a model without interaction or without cluster-level effects. Log marginal likelihoods were approximated with the *bridge sampling* algorithm (Gronau et al., 2017) using sufficient posterior samples (40 000). We also reported for the "winning model" the conditional and marginal coefficients of determination (R^2), which can be interpreted as measures of the variance explained by the full model (population and cluster-level effects) and the population-level terms only, respectively. We applied the definitions proposed by (Gelman et al., 2019) for Bayesian regression models, and summarized the posterior distributions of R^2 by their median and 95% highest density interval (HDI).

Effects of interest

To analyze in more details the interaction effect we examined, condition-wise, two meaningful estimates of the model: an estimated measure of sensory attenuation computed as the difference between predicted matched force and target force—at the average target force value—and the change in expected matched force for a unitary increase in target force (its slope, or marginal effect). The main advantage of Bayesian modeling is that these estimates can be derived directly from the full posterior distributions of the model's parameters, thus taking into account various sources of uncertainty. These estimates as well as their differences between conditions (i.e. marginal contrasts) were summarized by their median and 95% HDI, and further tested with Bayesian indices.

Indices of significance

Two Bayesian indices of effect existence and significance were used: the probability of direction and BFs. The probability of direction, abbreviated *pd* in the results, represents the certainty with which an effect is positive or negative, and is conceptually close to the frequentist *P*-value (Makowski et al. 2019b). The reference values suggest that an effect with pd < 0.95 is "uncertain," > 0.95 "possible," > 0.97 'likely', > 0.99 'probably exists' and > 0.999 "certainly exists" (Makowski et al. 2019b). BFs are used to compare the likelihood of the data given two competing models: an exact-point null hypothesis—in which the parameter of interest is not different from zero (or another value of interest)—and an alternative model allowing for a wider range of estimate values, as encoded in the prior distribution. The BF_{10} quantifies the evidence against the null hypothesis while $BF_{01} (= 1/BF_{10})$ quantifies the evidence in favor of the null hypothesis, an assessment that is typically not possible in frequentist statistics. Common guidelines suggest interpreting a BF below 3 as anecdotal or inconclusive evidence, between 3 and 10 as moderate evidence, between 10 and 30 as strong evidence, between 30 and 100 as very strong evidence, and above 100 as extreme evidence in favor of a model (Jeffreys, 1998).

Importantly, classical "treatment" contrast coding (comparison to a reference level) or "sum" contrast coding (all levels sum to zero) of categorical variables can lead to biases in prior distributions of their pairwise contrasts (or differences) for factors with three or more levels, such as "condition" in our model, thus affecting *post hoc* inference tests relying on priors such as BFs (Rouder et al., 2012, Makowski et al. 2019a). To avoid this bias, we used orthonormal factor coding (`contr.equalprior` from the R package `bayestestR`) and checked that it led to similar priors for "condition" levels and their contrasts.

Correlations between sensory attenuation and psychometric measures at baseline (T1)

Robust Bayesian correlations were run independently on each combination of psychometric scores or meditation variables (MAIA and FFMQ subdimensions, "lifetime," "daily," and "retreat" meditation experience) and the mean sensory attenuation (defined for each subject as $\textit{matched} - \textit{targetforce}$, and averaged over target force levels and trials) measured at baseline (T1). We ran this analysis on our condition of interest (*direct contact*) where sensory attenuation was supposed to be the highest, but also on *mediated contact* and *remote* conditions, as a sanity check. The mediated contact condition was thought to behave similarly as direct contact, whereas the remote condition was not expected to show sensory attenuation. Age, sex, and handedness were regressed out from variables of interest before running the correlations.

Briefly, a robust Bayesian correlation coefficient was obtained by modeling the relationship between each pair of variables (e.g.

sensory attenuation and FFMQ "Acting with awareness," with per-subject values) with a bivariate Student's t-distribution, robust to potential data outliers (Kruschke, 2014). We used the R package `rstan` to perform this analysis, using 4000 iterations and a transformed Beta(2, 2) prior on the correlation coefficient. For each pair of variables, the robust Bayesian correlation coefficient (named ρ) was summarized by the median of its posterior distribution, along with its 95% HDI. In a Bayesian framework, the existence of a correlation can be assessed with the probability of direction (*pd*, see "Measures of interest" section above for a description and threshold values), and its "significance," in the sense of "worthy of attention," can be assessed by examining the percentage of the *entire* posterior distribution of the correlation coefficient that falls within the region of practical equivalence (full ROPE). For a correlation, the ROPE is typically defined as between −0.05 and 0.05, boundaries equal to half the value of a negligible correlation (Makowski et al. 2019a). The full ROPE percentage is considered a continuous index of "significance" (Makowski et al. 2019b)—the lower its value, the more significant the effect is—but criteria can be defined, with values below 2.5% in full ROPE qualifying a "probably significant" effect, and below 1% a "significant" one.

Statistical modeling of longitudinal data - Linear mixed effect models

Given the complexity of our longitudinal data (three categorical predictors with two or three levels each and one continuous predictor), we chose to use linear mixed effects models via the R package `lme4` (Bates et al., 2015). This type of models has the advantage of using a hierarchical structure to fit population- (fixed) and cluster-level (random) effects—as in the Bayesian model for baseline data, see above—without the complex machinery of Bayesian inference, which can be very computationally demanding for complex designs, with outcomes quite difficult to interpret. Besides, as there were no major differences at baseline between direct and mediated contact conditions, we chose to focus on the main conditions of interest (direct contact and remote). We first ran a complete model with "target force" (1, 1.5, 2, 2.5, 3, 3.5 N), "condition" (*direct contact, remote*), "Time" (T1−***baseline***, T2 − ***retreat***, and T3 − ***follow − up***), "group" (*active*, *control*), and their interactions, as main predictors. We modeled a random intercept per subject and a random slope for each within-subject variable (Target force, Condition, and Time) per subject, giving the following formula for the full longitudinal model:

$$\begin{aligned}&Matched\ force \sim Target\ force \times Condition \times Time \times Group\\&+ (1 + Targetforce + Condition + Time \mid Subject) \qquad (2)\end{aligned}$$

Then, as the quadruple interaction was significant, we chose to dissect the full model into smaller models whose interactions were easier to analyze. We thus ran similar mixed models for the *active* and *control* groups separately (hence removing the "group" predictor from the previous equation), as well as for the *direct* and *remote* conditions separately (removing the "condition" predictor from both main and random effects). If the remaining interactions were significant, we ran appropriate post-hoc pairwise t-tests on target force slope, with the Tukey HSD ("Honest Significant Differences") multiple comparison correction for confidence intervals and *P*-values, using the R package `emmeans`. We report in the Results section the *marginal* contrasts between time, group, or condition levels (e.g. difference of target force slope between time pairs, with all other predictors marginalized or averaged over) and their corrected significance.

While our sample size was comparable with previous cross-sectional force-matching studies (e.g. Shergill et al. (2005), Pareés et al. (2014), Shergill et al. (2014)) and constrained by the logistical challenge of a 10-day residential retreat organized during the COVID-19 pandemic, we conducted a simulation-based power study to estimate the magnitude of longitudinal change that could be reliably detected, under various scenarios of inter-individual variability (see Supplementary Materials for details on the procedure and assumptions). We found that our sample size achieved a statistical power of at least 80% for Group × Time interaction effects larger than 0.3 N, under the condition of low inter-individual variability (i.e. an effect in the expected direction for 90% of the participants, see Supplementary Fig. S1). As a comparison, we can note that Wolpe et al. (2016) study on aging reports an increase of overmatching force of about 0.15 N/decade and that between-group contrasts reported in the literature range between 0.2 and 0.8 N.

Statistical modeling of phenomenological data

Responses to our phenomenological scales resemble Likert ratings which, despite being ordinal data, have often been modeled in the literature as continuous ones. Yet, recent evidence suggests that the original ordinal nature of the data should be accounted for by assuming that they belong to an underlying thresholded cumulative normal distribution, and thus better modeled with cumulative link (mixed) effects models (Liddell and Kruschke, 2018, Taylor et al., 2022). We used again the R package `brms` to fit separate Bayesian ordinal regression models (Bürkner and Vuorre, 2019) for each phenomenological scale (*saliency*, *confidence*, *movement*, *attention*, and *tension*), with the probit link function, which assumes the underlying latent variable to be normally distributed (whereas the logit link function assumes a logistic distribution). We chose to use the pooled data from all conditions, as we did not expect major differences between conditions on these scales and we were more interested in the longitudinal effect of the retreat. This allowed us to model the repetition of phenomenological measures throughout the same measurement session (i.e. there were 2 blocks of 15 trials per condition, leading to 6 blocks per time point). Phenomenological ratings were thus modeled as a monotonic effect of "block" number, plus a 'group' (*active*, *control*) by "time" (T1, T2, and T3) interaction, as well as a random intercept and random 'time' slope per subject. This led to the following formula for each scale:

$$Rating_{scale} \sim Block + Group \times Time + (1 + Time \mid Subject)$$

We ran *post hoc* pairwise t-tests between times for each group, and between groups for each time point, again using the `emmeans` R package and the Tukey HSD multiple comparison correction. Estimates were summarized by their mean and 95% confidence intervals (CI).

Correlations between sensory attenuation and phenomenological dimensions

We examined correlations between the mean sensory attenuation measured in our participants, and their subjective ratings of phenomenological dimensions (saliency, confidence, attention, movement, tension) collected during the force-matching task. As no meaningful effects of the meditation retreat on the phenomenological ratings were observed, we pooled together the data from all subjects (n = 41, both groups), time points (T1, T2, and T3), conditions (direct, mediated, and remote), and the two experimental blocks of a session, leading to 658 observations in total. The coefficient of correlation was estimated with the same statistical method as for the baseline measure (using a bivariate t-student distribution, see above), without regressing out trait covariates (age, sex, handedness) but correcting for inter-subject variability by centering individual measures on the subject's mean.

Results

Sensory attenuation at baseline (T1, pre-intervention)

Bayesian modeling of force data

We analyzed the matched forces intensities at the baseline session for all participants across the two groups (n = 41, after the removal of an outlier subject) with a hierarchical Bayesian regression model. This model accounted for fixed or population-level effects of target force (continuous predictor: 1.0–3.5 N), condition (categorical predictor: *direct contact*, *mediated contact*, and *remote*), and their interaction, as well as random or cluster-level effects of target force and condition per subject. Inspection of the model diagnostics confirmed good mixing and convergence of the MCMC chains, and satisfying posterior predictive checks (Supplementary Table S2 and Supplementary Fig. S2). Bayesian model comparison to the reduced models gave extreme evidence in favor of both the interaction term and cluster-level effects ($\mathrm{BF}_{10} > 10^6$). The proportion of variance explained by the winning interaction model was consequently large (Conditional R^2: median = 0.74, 95% HDI [0.73, 0.75]) and greatly reduced without cluster-level random effects (Marginal R^2: 0.35 [0.29, 0.41]).

We further examined the interaction effect by computing for each condition a predicted measure of sensory attenuation (predicted matched force – target force) at average target force. The data provided very strong evidence for the expected effects: a sensory attenuation in the direct contact condition (predicted matched force – target force = 0.94 [0.55, 1.31], pd = 100.0%, BF_{10} = 788), and force *underestimation* for the remote condition (−0.40 [−0.56, −0.24], pd = 100.0%, BF_{10} = 113). For the mediated condition, however, despite a *pd* suggesting a likely positive sensory attenuation, the BF did not reach the threshold for moderate evidence (0.45 [0.08, 0.78], pd = 99.2%, BF_{10} = 0.59). With regards to marginal contrasts between conditions, the remote condition displayed much lower sensory attenuation than the direct and the mediated contact conditions (direct > remote: 1.33 [0.96, 1.71], pd = 100%, $\mathrm{BF}_{10} > 1000$; mediated > remote: 0.85 [0.33, 1.37], pd = 100%, BF_{10} = 11). On the other hand, the comparison of direct and mediated conditions for sensory attenuation was not conclusive (direct > mediated: 0.48 [0.15, 0.8], pd = 99.7%, BF_{10} = 1).

We also examined the differences between conditions in the expected change of matched force for a unitary increase in target force, i.e. its marginal effect or slope (Fig. 3). The slope for the target force was significantly different between the remote condition and the two others (direct > remote: 0.16 [0.08, 0.23], pd = 100%, BF_{10} = 14; mediated > remote: 0.26 [0.19, 0.33], pd = 100%, $\mathrm{BF}_{10} > 1000$), but there was a moderate evidence against a difference between the direct and mediated conditions (direct > mediated: −0.1 [−0.18, −0.03], pd = 99.6%, BF_{01} = 3.22). Interestingly, simple effects of the conditions on the target force slope showed a slope significantly less than 1 in the direct and remote conditions (direct: 0.82 [0.73, 0.90], pd = 100%, BF_{10} = 17; remote: 0.66 [0.58, 0.75], pd = 100%, $\mathrm{BF}_{10} > 1000$), while the slope in the mediated condition was not different from 1 (0.92 [0.84, 1.01], pd = 96.8%, BF_{01} = 16). In other words, the *absolute* overestimation of force decreased with the magnitude of target force in the direct condition, but remained constant in the mediated condition. In the remote condition, the force was increasingly *underestimated* at larger target forces.

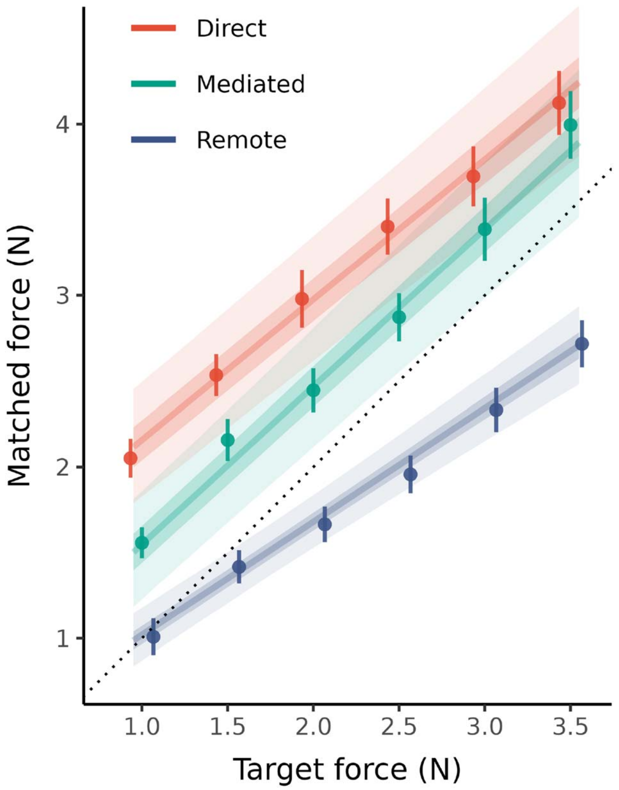


Figure 3. Average matched force as a function of target force and conditions at T1 (baseline). Data was averaged over all trials and subjects (except one outlier, n = 41) without group distinction. Error bars around observed mean matched forces (dots) represent within-subject variance (after removal of the between-subject variance) as 95% confidence intervals. Population-level posterior predictions from the Bayesian model are superimposed, with lines representing the median over all MCMC draws and the inner and outer ribbons displaying, respectively, their 50% and 95% credibility intervals. Participants reproduced the force by pressing their right hand index finger either (a) directly on their receiving left index fingernail (*direct contact* condition, red), (b) on the lever resting upon their left index fingernail (*mediated contact* condition, green), or (c) on a sensor placed 20 cm to the right of the receiving left index finger, which controlled the lever pressure via a motor (*remote* condition, blue). Bayesian modeling showed that target force intensity and condition had interacting effects on matched force, with meaningful differences between conditions in predicted sensory attenuation (defined as the difference between predicted matched force and target force) and in the slope of the target force effect (see main text and Supplementary Table S3).

In summary, data from all subjects pooled together at the baseline session (T1) exhibit differences between our experimental conditions, confirming the replication of the sensory attenuation effect: higher force overestimation when fingers are physically in contact (direct condition) compared to when fingers are at distance (remote condition).

Correlation with psychometric measures

Robust Bayesian correlation analyses were performed between the mean sensory attenuation (matched – target force) measured at T1 and psychometric variables of interest (MAIA and FFMQ sub-dimensions, and "lifetime," "daily," and "retreat" meditation experience). Only the "Acting with awareness" facet of the FFMQ

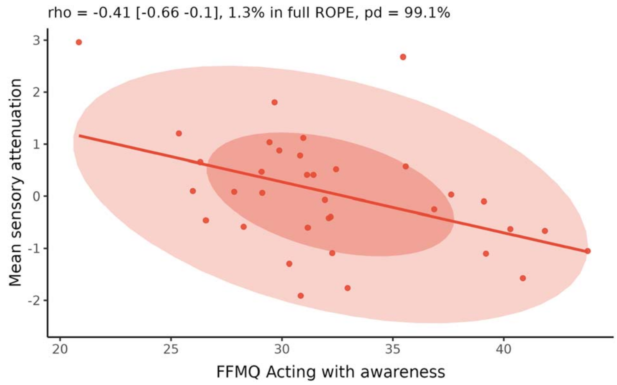


Figure 4. Robust Bayesian correlation between sensory attenuation, computed as **matched – target force** for the *direct contact* condition, and the "Acting with awareness" facet of the FFMQ, both measured at T1 before any meditation intervention. Each dot represents the data of a participant averaged over target force levels, the line is the best linear fit between the two variables and the dark inner (pale outer) ellipse is the area containing 50% (95%) of the posterior bivariate Student's t-distribution.

showed a meaningful negative correlation with sensory attenuation in the *direct contact* condition ($\rho_{\text{median}} = -0.41$, 95% HDI [−0.66, −0.1], N(subjects) = 35, Fig. 4). Bayesian indices of existence and significance suggest that this effect is likely real (pd = 99.1%) and can be considered as significant (1.3% of the entire posterior distribution for ρ lies within the ROPE, see Methods for definition of Bayesian indices). FFMQ 'Acting with awareness' was also negatively correlated with sensory attenuation in the *mediated contact* condition ($\rho_{\text{median}} = -0.38$ [−0.66 −0.09], 1.8% in ROPE, pd = 98.8%, $N = 37$) but not in the *remote* one ($\rho_{\text{median}} = -0.08$ [−0.39, 0.25], 20.9% in ROPE, pd = 68.5%). On the other hand, the FFMQ 'Observe' dimension was *positively* correlated with sensory attenuation in the *remote* condition, although the Bayesian indices suggest a likely effect of undecided significance ($\rho_{\text{median}} = 0.32$ [0.01, 0.58], 3.74% in ROPE, pd = 97.3%, $N = 39$). No other correlations between sensory attenuation and FFMQ/MAIA dimensions or meditation experience measures showed meaningful posterior correlation coefficients.

Longitudinal effects of the meditation retreat, during (T2) and post-intervention (T3)

Linear mixed modeling of force data

In order to simplify the statistical modeling of the longitudinal effects, and given that the mediated condition showed similar results to the direct contact one at baseline (T1), we restricted the longitudinal analyses to the direct contact and the remote conditions. Statistical modeling of matched force across groups (*active, control*), time measurements (*T1, T2, T3*), conditions (*direct contact, remote*) and target forces (1–3.5 N, continuous predictor) with a linear mixed model revealed a significant quadruple interaction between these four independent variables ($F(6542) = 5.94$, $P = .0026$). To interpret this high-order interaction, and given that the group variable was not involved in any lower level interaction, we first split the dataset into "active" and "control" groups and model them separately (Fig. 5a). In each group, we found a significant triple interaction between target force, time and condition (active: $F(2, 3028) = 3.71$, $P = .025$; control: $F(2, 3516) = 7.35$, $P = .0007$). As target force was modeled as a continuous predictor, we then performed *post hoc* tests to look at the influence of time and condition on target force slope (Fig. 5b). In the control group, we found a clear evidence for a constant decrease of target force slope over time, in the direct contact condition only (T1 > T2: estimated slope difference = 0.13, 95% CI = [0.02, 0.24], $t(3519) = 2.69$, $P = .020$; T1 > T3: 0.25 [0.14, 0.37], $t(3521) = 5.18$, $P < .0001$; T2 > T3: 0.12 [0.01, 0.23], $t(3512) = 2.64$, $P = .023$), suggesting that repetitions of the task decreased sensory attenuation for greater force levels. In the active group, *post hoc* tests did not reveal a difference between T1 and T2 in the direct contact condition (T1 > T2: −0.08 [−0.21, 0.04], $t(3036) = -1.62$, $P = .24$), but a steeper slope at T2 compared to T3 (T2 > T3: 0.18 [0.06, 0.31], $t(3036) = 3.45$, $P = .0016$). These effects were present only in the direct contact condition, with no significant differences across time for the remote condition in both groups.

To summarize, in control participants we observed a habituation effect for what concerns sensory attenuation, with decreasing sensory attenuation at high forces at the second and third measurement time point (target force slope T1 > T2 > T3). In contrast, active participants during the meditation retreat showed a preserved sensory attenuation at T2 (no significant difference between T1 and T2 in target force slope), but they also showed habituation once the retreat was over, when measured three weeks after the retreat (target force slope T2 > T3).

To gain further insight into these findings, we ran additional linear mixed models for the direct and remote conditions separately. These sub-models allowed us to assess potential differences across groups along time for a given condition, which we could not test in the previous sub-models. For the remote condition, we found a significant triple interaction between time, group and target force ($F(2, 3274) = 4.72$, $P = .009$) and ran *post hoc* tests on the slope of the continuous predictor (target force). We observed a significantly higher *remote* condition slope for the active group compared to the control one at T1 (−0.13 [−0.25, −0.017], $t(59) = -2.3$, $P = .025$). For the direct contact condition, the triple interaction did not reach significance ($F(2, 2316) = 2.99$, $P = .0503$) and indeed *post hoc* tests did not reveal group differences at any time points (nor time differences between groups), neither in target force slope nor in marginal contrasts on the average target force. This null result contradicts our expectations of, at least, a difference between groups in somatosensory attenuation at the T2 time point, when active participants were immersed in an intensive 10-day mindfulness meditation retreat. Potential explanations for this absence of effect and implications for future studies will be covered in discussion.

Changes in phenomenology and correlation with sensory attenuation

Bayesian ordinal regression models of phenomenological ratings identified a meaningful effect only for the "Attention" scale, in which the group by time interaction was driven by decreased ratings at T2 compared to T1 in the control group (T1 > T2: estimated difference = 1.17, 95% HDI = [0.52, 1.82], pd = 100%, $BF_{10} = 14.4$). None of the other scales showed significant effects.

Bayesian correlation analyses between sensory attenuation and phenomenological ratings over all subjects, time points, conditions and blocks (658 total observations, corrected for inter-subject variability) revealed negative relationships of both "Saliency" and "Confidence" with sensory attenuation, "significant" in terms of the percentage of the posterior distribution within the ROPE, but weak in absolute value (ρ_{saliency}: median = −0.18, 95% HDI [−0.25, −0.1], 0.09% in ROPE, $pd = 100\%$; $\rho_{\text{confidence}}$: −0.21, [−0.28, −0.13], < 0.01% in ROPE, $pd = 100\%$) — see Fig. 6. Phenomenological scales were moderately correlated between them (see Supplementary Table S4 for the detailed estimates).

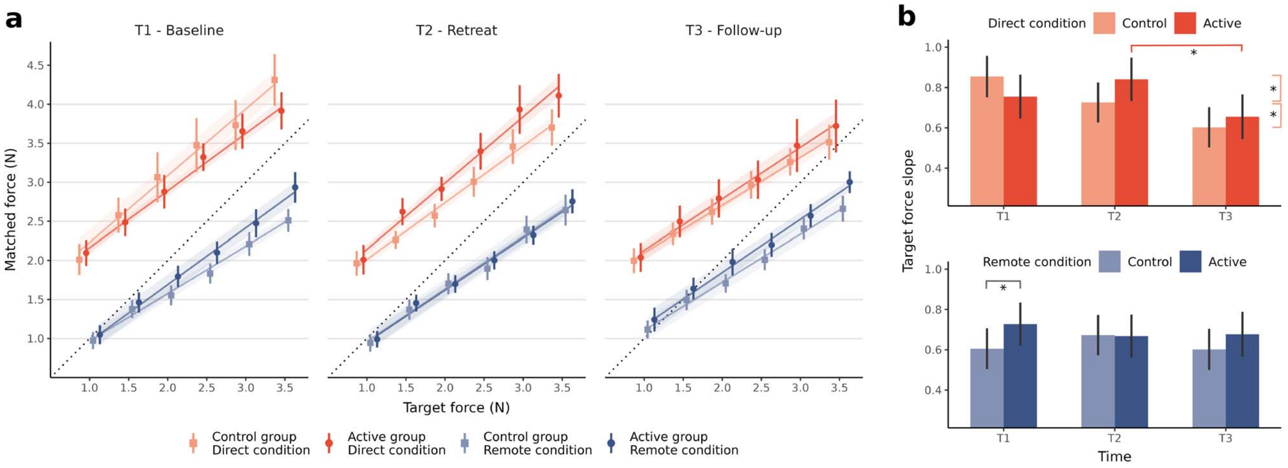


Figure 5. Longitudinal effect of the meditation retreat. (a) Observed mean matched force against target force for direct (red) and remote (blue) conditions, active (dark dots/lines) and control (pale squares/lines) groups, at the three measurement times of the study (T1: baseline; T2: retreat; and T3: follow-up). Control participants underwent T1, T2, and T3 measurements with the same time intervals as active participants, but before their participation to the meditation retreat. In the graphs, data points have been horizontally jittered for better clarity (i.e. the only target force values in the study were 1, 1.5, 2, 2.5, 3, and 3.5 N). Error bars around observed values represent within-subject variability (after removal of the between-subject variance) as 95% confidence intervals. Predictions from the full linear mixed model are plotted as lines, with their 95% within-subject confidence intervals (ribbons). The dotted line displays the theoretical case of perfect force-matching, where matched force equals target force. (b) Estimated marginal means of target force slope, as well as their 95% within-subject confidence intervals (vertical lines), were computed from the full linear model predictions. Analysis of sub-models marginal effects show reduce sensory attenuation at high forces for the *direct* contact condition in *control* participants (pale red) from T1 to T2 to T3 (decreasing target force slope). This effect is seemingly suspended by the participation to the meditation retreat in *active* participants (dark red) where sensory attenuation at high forces is maintained at T2 (no difference in slope to T1), but happen at T3 (decrease in slope). Yet, contrary to our expectations, there was no difference in matched force between control and active participants at T2, neither in marginal means at average target force nor in target force slope. * *significant difference (P <.05) between target force slope for a given time, group and condition contrast.*

"Saliency," "Confidence," and "Attention" were all mutually positively correlated ; "Movement" and "Tension" were also positively correlated, but negatively correlated to the former three dimensions.

Discussion

Recently, there has been a surge of conceptual proposals to adopt the framework of predictive processing and active inference to develop mechanistic models of attentional and metacognitive processes in meditation (Lutz et al., 2019, Pagnoni, 2019, Deane et al., 2020, Limanowski and Friston, 2020, Manjaly and Iglesias, 2020, Laukkonen and Slagter, 2021, Pagnoni and Guareschi, 2021, Ramstead et al., 2022, Becattini et al., 2025). While these approaches are inspiring, explicit simulations or experimental verifications are largely to be developed (but see Sandved-Smith et al. (2021), Dor-Ziderman et al. (2025)). Here, for the first time, we tested a hypothesis born out of an active inference perspective on meditation practices, using a longitudinal design. We focused on somatosensory attenuation as assessed with the force-matching paradigm and, more specifically, on the putative changes that an intensive meditative retreat would induce with regard to this process. Overall, we predicted that the heightened awareness of bodily sensations cultivated through meditation practice would enhance the precision of somatosensory signals, thereby partially offsetting natural somatosensory attenuation during task performance.

The present study yielded three main findings. First, contrary to our expectations, participants in the intensive 10-day meditation retreat did not show evidence for a general reduction in sensory attenuation compared to the waiting list group. Second, in line with our expectations, we also found that sensory attenuation correlated with certain psychometric measures of mindfulness meditation at baseline. Finally, we observed that, within a session, sensory attenuation decreased with larger target forces. This effect showed, however, a peculiar interaction of group and time: it increased its magnitude from T1 to T2 to T3 in the waiting list group, but remained stable in the active group from T1 (baseline) to T2 (retreat), and increased only from T2 to T3 (follow-up). Below, we discuss these findings in detail, after a brief examination of the methodological validation of our paradigm.

Replication of the somatosensory attenuation effect

One of the aims of our study was to verify the replicability of previous findings with our protocol, which introduced a novel experimental condition using a device allowing for direct, unmediated contact between the force-applying and the receiving fingers. We confirmed the presence of a sensory attenuation effect in the baseline data (T1), i.e. before any meditation intervention, across all participants. Using hierarchical Bayesian modeling, we observed that participants overshot the target force level in the direct contact condition but not in the remote one. While the mediated contact condition also showed a trend for the presence of sensory attenuation, the effect was not statistically conclusive. For the direct contact condition, the sensory attenuation manifested in our novel experimental setup showed an amplitude of 0.94 Newtons (95% HDI [0.42, 1.4]), similar to the ones reported in most of the force-matching literature. For example, the largest study to date, on 332 individuals of all ages Wolpe et al. (2016), found a mean force overcompensation of 1.20 N (s.d. = 0.89 N, on a 1 to 2.5 N target force range). Interestingly, however, our data showed a sensory attenuation effect that varied with the target force intensity: the matched force slopes were significantly inferior to 1 in the direct contact condition (but not in the mediated contact condition, see Fig. 3 and Supplementary Table S3),

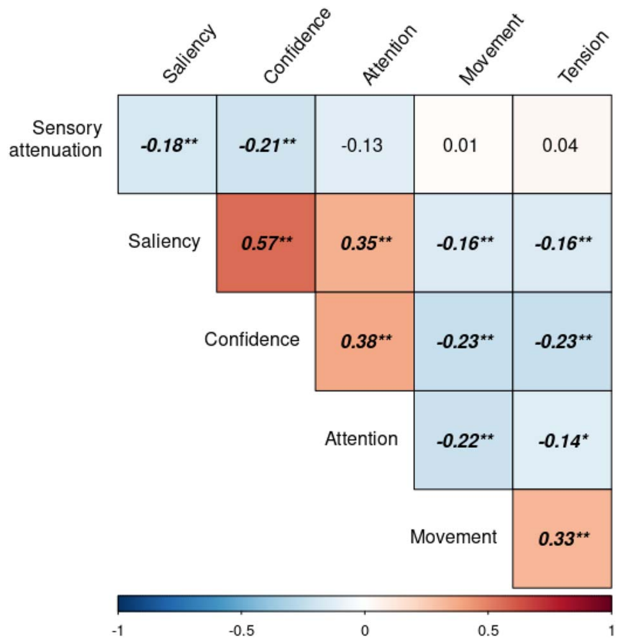


Figure 6. Robust Bayesian within-subject correlations between sensory attenuation and phenomenological dimensions assessed during the experiment. We used data from all subjects, conditions, time points, and experimental blocks, leading to 658 observations for each pair of variables. The colorbar displays the median value of the posterior distribution of the correlation coefficient. "Significance" levels: * means that less than 2.5% of rho's posterior distribution is in the ROPE (−0.05,0.05), ** < 1% in full ROPE. Sensory attenuation shows a significant but weak correlation with 'Saliency' and 'Confidence'. All phenomenological variables are moderately correlated between them, in particular "Saliency," "Confidence," and "Attention" are positively correlated, while 'Movement' and 'Tension' form a second positive cluster negatively correlated with the first one.

suggesting greater sensory attenuation at lower than higher force levels in this condition. While this effect was actually apparent in various force-matching studies (Bays et al., 2008, Palmer et al., 2016, Kilteni and Ehrsson, 2017, McNaughton et al., 2021), few of them investigated it in detail. Applying the classical force-matching paradigm on sample sizes of 18 and 25 participants respectively, Palmer et al. (2016) and McNaughton et al. (2021) found a significant decrease of sensory attenuation at higher forces too. On the other hand, Walsh et al. (2011) identified constant force overestimation (target force slope not different than 1) during what they termed "passive" force-matching (a condition similar to the classic paradigm). Although the range of target force intensities used in that study was much larger than the one classically used in force-matching paradigm (1 to 10 Newtons), the small sample size ($N = 8$) may have limited the ability to detect the influence of force level.

To our knowledge, no theoretical explanation was given for this effect despite its potential importance in the sensory attenuation phenomena. We propose a simple explanation, based on psychophysics theories of magnitude estimation in other sensory modalities or tasks, and their recent translation and integration to Bayesian accounts of perception such as Active Inference. Petzschner et al. (2015) summarized well a known bias in magnitude estimation called the regression effect or "central tendency of judgment": magnitude estimates are biased toward the mean or central value of a fixed set of tested magnitudes, leading to overestimation of magnitudes smaller than the mean and underestimation of magnitudes greater than the mean. The decrease in sensory attenuation with increasing target force intensity we observed in our data, could be well accommodated by this mechanism. In the "control" condition of force-matching tasks ("remote" in our case but more commonly with the use of a slider)—where sensory attenuation is not supposed to be present—this effect is directly visible as an *underestimation* of reproduced force at higher target force levels (below the perfect match or identity line, see Fig. 3. In the direct contact condition, however, the combination of these effects with sensory attenuation should produce a mitigation of sensory attenuation at stronger target forces, which is exactly what we observe. However, under a "regression to the mean" explanation, we would also expect the opposite effect to occur at lower force levels. While this seems to be the case for the direct contact condition (higher relative sensory attenuation at low forces and constant decrease), we do not see the expected force *overestimation* at low force levels in the remote condition for our data. This could be due to the use of a pressing at distance condition instead of the classical "slider" control condition, the overestimation being seemingly present in previous force-matching studies (Shergill et al., 2003, 2005, Teufel et al., 2010, Palmer et al., 2016, Wolpe et al., 2016, Kilteni and Ehrsson, 2017).

Meditation and changes in precisions, a (complex) Active Inference perspective

We will now elaborate on the initial rationale for this study and discuss the implications of the partial negative findings for the design of future studies. The genesis of this project lies in the recognition that a careful arrangement and regulation of bodily posture is instructed in most meditative practices, with the rationale that it fosters mental quiescence and stillness (Woods et al., 2020). The intentional suspension of overt action—for the duration of the sitting session—is thought to facilitate the monitoring and regulation of cognitive activity and emotions during meditation. These phenomenological features of mindfulness meditation have begun to be articulated in terms of active inference in recent years (Farb et al., 2015, Lutz et al., 2019, Laukkonen and Slagter, 2021, Pagnoni and Guareschi, 2021). According to this perspective, the voluntary allocation of attention to the body during meditation aids in calming the mind by shifting precision away from higher-order habitual, compulsive cognitive processes. Within this framework, our study aimed to test the hypothesis that the heightened awareness to bodily sensory signals cultivated during the meditative retreat would reduce the amplitude of sensory attenuation in the force-matching paradigm.

Our findings did not provide a straightforward confirmation of our initial hypothesis. On the one hand, we did not observe the expected general reduction in sensory attenuation, when averaged over target force intensities, following the meditative retreat (T2 vs. T1). On the other hand, the data suggested a subtler effect of the retreat on the force-matching performance, related to either the formation or the influence of prior expectations on target force under a Bayesian account. More specifically, we observed at baseline (T1) a downward tilting of the regression line for the direct condition with respect to the identity line, in the graphs of matched force vs. target force (i.e. target force slope < 1, Fig. 5 and Supplementary Table S3). This "regression to the mean" effect can be putatively explained by the fact that, in the course of a task session, the participants accumulate evidence for the average value of the target force (2.25 N), which biases their estimate for the currently presented target force (and thus their exerted matching force) toward greater values, when the target force is smaller than the mean—and toward smaller values, when the target force is larger (Petzschner et al., 2015). At the time of the second measurement one week later (T2), the memory of the first measurement can be expected to increase the influence of a prior centered on the mean force, leading to a stronger regression effect (i.e. the regression line for the matched force should tilt downward even more), and this trend should continue at the third measurement 3 weeks later (T3). In fact, this is what we observed for the control group (target force slope at T1 > T2 > T3, Fig. 5) but, notably, not for the active group during the period of meditative retreat (target force slope at T1 not different from T2), suggesting that the intensive practice of meditation suspends, at least partially, the process of prior updating for the target force—or modulates its relative precision *vis-à-vis* sensory input—following repeated exposure to the task. While we did not anticipate this specific effect—and the experiment was not originally designed to test it—it aligns well with the notion that meditative practice facilitates perceiving things "afresh," weakening the influence of engrained priors and maintaining, so to say, a "beginner's mind" (Suzuki, 2006, Pagnoni and Guareschi, 2021). Whether intensive meditation practice prevents prior updating, or rather modulates its associated precision (or both), remains to be properly tested. Recently developed computational models of sensory attenuation could offer promising avenues to answer such complex questions (Idei et al., 2022, Eckert et al., 2025).

A further potential explanation, not necessarily mutually exclusive with the one proposed above, is that intensive meditative practice enhanced attention to both bodily sensations *and* one's own actions. A role of top-down cognitive processes in reducing sensory attenuation in the force-matching task has been previously proposed for patients who exhibit symptoms of paralysis or dystonia without any evidence of neurological damage (Pareés et al., 2014, Limanowski et al., 2024). In this perspective, when engaging in the force-matching task, the active group may have paid more attention to perform an accurate gesture, compared to the control group, thus increasing the precision of their motor predictions over and above a possible decrease in sensory attenuation. This is reasonable, as it could be argued that the most radical change that participants undergo during a retreat concerns indeed their habitual behaviors and actions, with the necessary corollary enhancement of regulatory and monitoring processes. If this *post hoc* interpretation is correct, mindfulness-based meditation practices may exert two opposing effects on sensory attenuation in the force matching paradigm. The monitoring of bodily sensations, as cultivated in some of these practices, could increase attention to, and therefore the precision of, somatosensory signals in the receptive finger, leading to a reduction in sensory attenuation, as initially predicted. Conversely, the monitoring of motor execution could enhance the precision of motor predictions, increasing sensory attenuation. Different practices may activate one mechanism or the other to varying degrees. Unfortunately, the design of our study did not allow us to disentangle these two putative effects.

Interestingly, individual trait measures of mindfulness—specifically, the FFMQ facet "Acting with awareness"—did correlate negatively at baseline (T1) with the average sensory attenuation in the direct condition. In other words, self-reported awareness of one's own actions was associated with a decreased attenuation of their sensory consequences. This pattern of inter-individual variability is reflected at the within-subject level, as we found that self-reported saliency of finger sensations was positively correlated with confidence in force replication, and both were negatively correlated with sensory attenuation. This finding provides direct phenomenological evidence for the role of somatosensory precision in the sensory attenuation effect.

Limitations and future perspectives

This work has a number of limitations that could be addressed in future studies. Concerning the force-matching task, explaining the decrease in sensory attenuation with increasing target force by a regression-to-the-mean effect may only provide an incomplete picture, as we have not observed the expected overestimation at lower force levels in our control condition (but see visual results from Shergill et al. (2003, 2005), Teufel et al. (2010), Palmer et al. (2016), Wolpe et al. (2016), Kilteni and Ehrsson (2017) with the classic slider condition). Clarifying this issue will require a systematic investigation of the dependency of sensory attenuation on the target force, which has been largely missing in previous studies. Another effect that we did not expect, as it had never been reported to date (at least to our knowledge), was the increase of this regression effect, revealed in our waiting list group, after repetition of the task at one and four weeks. Our design aimed to test the longitudinal, state-related effect, of intensive meditation practice on already experienced practitioners. Testing a potential trait effect of meditation practice on sensory attenuation would have required the inclusion of a third, meditation-naïve, group. Thus, whether the observed effect extends to the general population, but also across tasks and sensory modalities, remains to be clarified. It should also be noted that the assessment of trait effects of meditation practice using a third sample of non-meditators is quite problematic because of all the caveats of a cross-sectional design (confounding causal factors, self-selection biases, etc).

Concerning our meditation manipulation, the instruction we gave to participants during the force matching task, of maintaining awareness to their sensations and movements, may also not have been specific enough. Given the putative opposite effect on sensory attenuation of focusing attention on the accuracy of the motor act and on the pressure sensations on the finger—which we proposed as one potential explanation for our findings—investigating such experimental manipulation in future research could indeed provide crucial insights. This could be operationalized either with distinct meditative instructions such as focused-attention and open-monitoring meditations, or by studying very specific meditative states causing the dissolution of perceived bodily boundaries, which has been speculated to rely on a modulation of somatosensory attenuation (Ciaunica, 2024, Becattini et al., 2025). On this line, recent proposals highlighted the potential role of a failure of sensory attenuation in depersonalization disorders (Ciaunica et al., 2022), and drew a parallel with depersonalization-like experiences occasionally arising in some deconstructive meditation practices (Ciaunica et al., 2021). While compelling, this hypothesis is not directly applicable to the present study, which focused exclusively on attention-based meditation practices (for a review of different types of meditative practices, see Dahl et al. (2015)). Finally, phenomenological questions asked during the task could be more refined and more frequent to better capture the complexity of attentional and physiological experiences during meditation practice (Abdoun et al., 2025).

To conclude, our exploratory study validated a novel force matching paradigm enabling direct finger contact, and highlighted the value of collecting fine-grained first-person data to better constrain interpretations of behavioral results (see Lutz et al. (2024), for a review of this methodology). While our findings did not directly support our initial hypothesis, they revealed an unexpected potential effect of the meditative retreat on priors' formation or the modulation of priors' relative precision. They also provide insight into possible theoretical refinements, interesting new research avenues and improved experimental designs for future replications.

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Author contributions

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Supplementary data

Supplementary data is available at *Neuroscience of Consciousness* online.

Conflict of interest

None declared.

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Data availability

Data and code to replicate the presented analyses are available on the Open Science Framework: https://osf.io/4a7bf/overview.

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