Pupil dilation reveals the intensity of touch

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Abstract

Touch is important for many aspects of our daily activities. One of the most important tactile characteristics is its perceived intensity. However, quantifying the intensity of perceived tactile stimulation beyond subjective self-reports remains challenging. Here, we show that pupil responses can objectively index the intensity of tactile stimulation in the absence of overt participant responses. In Experiment 1 (n=32), we stimulated three reportedly differentially sensitive body locations (finger, forearm, calf) with a single tap of a tactor while tracking pupil responses. Tactile stimulation resulted in greater pupil dilation than a baseline without stimulation. Furthermore, pupils dilated more for the more sensitive location (finger) than for the less sensitive locations (forearm, calf). In Experiment 2 (n=20) we extended these findings by manipulating the intensity of the stimulation with three different intensities, here a short vibration, always at the little finger. Again, pupils dilated more when being stimulated at higher intensities as compared to lower intensities. In summary, pupils dilated more for more sensitive parts of the body at constant stimulation intensity and for more intense stimulation at constant location. Taken together, the results show that the intensity of perceived tactile stimulation can be objectively measured with pupil responses – and that such responses are a versatile marker for touch research. Our findings may pave the way for previously impossible objective tests of tactile sensitivity, for example in minimally conscious state patients.

Introduction

Touch perception is central to many aspects of our daily lives. We use it to detect a mosquito on our arm, to comfort a friend, or to control the amount of pressure we apply when grasping an object. Our perception of a touch has many different characteristics, and it's intensity is one of them. Perceived touch intensity is influenced by a number of factors. It depends on stimulus characteristics, such as the amount of pressure applied to the skin, but also on non-stimulus characteristics, such as the sensitivity of the part of the body being touched (Weinstein, 1968). The ability to perceive touch, and differences in perceived touch intensity are typically assessed using psychophysical methods involving overt motor or verbal responses (e.g. Fritz & Zimmermann, 2023; Kusnir et al., 2023). While this has many advantages, it does not allow for the assessment of more implicit representations and prevents the testing of touch perception in situations where overt verbal and motor responses are not possible.

Changes in pupil size are a promising candidate for providing an objective psychophysiological index. The eye's pupil does not only respond to changes in low-level vision, but also reflects attentional processing (see Strauch et al., 2022 for a review). More specifically, pupil size is arguably the most sensitive psychophysiological indicator of the mental effort involved in any given physical or cognitive process. This is likely due to the close link between pupil size and activity in the norepinephrinergic locus coeruleus in the brainstem (Alnaes et al., 2014; Aston-Jones & Cohen, 2005; Joshi et al., 2016; Murphy et al., 2014; Schwarz et al., 2015; Strauch et al., 2022). The locus coeruleus has widespread projections throughout the brain and is thought to be involved in the coordination and collaboration of neural populations, including flexibly switching between circuits and synchronizing activity (Dahl et al., 2022; Poe et al., 2020; Wainstein et al., 2022). As more intense tactile perception should go hand in hand with more intense processing thereof, we predicted that pupils would dilate in response to tactile stimulation, and that the more intense the stimulation is perceived the more dilation would occur.

The effects of pain on pupil size were described already more than a century ago (Bumke, 1911) and have been reported in a variety of populations (Drummond & Clark, 2023; Ji et al., 2022; Macchini et al., 2022; Sillevis et al., 2021; Yılmaz, 2022). Only a few modern-day studies have directly investigated the effects of *non-painful tactile stimulation* on pupil size, mostly in animals (Gusso et al., 2021). The studies in humans have shown that pupils dilate in response to tactile stimulation, with some indications that the magnitude of this dilation is modulated by whether the stimulus is consciously perceived (Gusso et al., 2022), the stroke speed (van Hooijdonk et al., 2019), the frequency of vibrotactile stimulation (Mückschel et al., 2020), and the type of the material that participants actively touched (Bertheaux et al., 2020). While these findings suggest that pupil size changes scale with stimulus intensity, previous studies suffer from serious methodological limitations, such as the non-automated delivery of tactile stimulation (Bertheaux et al., 2020; van Hooijdonk et al., 2019). These shortcomings make it impossible to draw substantive conclusions, for example about the temporal course of tactile processing. However, if pupil size can indeed serve as a reliable indicator of tactile perception, this would allow for the objective investigation of a variety of questions: For example, how intensely is tactile stimulation processed with differing degrees of attention paid to a particular part of the body, or as a function of conscious perception (Gusso et al., 2022)? How strong is the processing of tactile stimulation as a function of stimulation intensity and frequency, receptor density, or skin and receptor type in healthy subjects and in pathology? Does pupil size show residual processing of tactile stimulation intensity in patients with somatosensory impairments after brain lesions?

In two experiments, for which the overarching hypotheses were pre-registered, we investigated whether and how well changes in pupil size can indicate the objective intensity of tactile processing – and thus the basis for how intensely tactile stimulation is perceived. In Experiment 1, we measured pupil size in response to stimulation by a tapper on body parts which differ in tactile sensitivity (Weinstein, 1968) in addition to a non-stimulation baseline. We expected more dilation with stimulation than without stimulation, and a greater increase in pupil size for more subjectively sensitive body parts than for less sensitive body parts. In Experiment 2, we stimulated only the little finger, but at different vibration intensities and against a non-stimulation baseline. Again, we expected more dilation with stimulation than without stimulation, and more pronounced effects with more intense stimulation than with less intense stimulation. Finally, we expected differences in pupil size to reflect differences in subjective tactile sensitivity as assessed by von Frey filaments (Experiment 1) and differences in tactile discrimination performance (Experiment 2).

Experiment 1

Materials and methods

The research and consent procedures were conducted in accordance with the standards of the Declaration of Helsinki and were approved by the Ethics Committee of the Faculty of Social and Behavioural Sciences of Utrecht University (protocol number 23-0229). Overarching hypotheses were preregistered. Participants were recruited between March and May 2023. As the effects were of unknown size, no power estimate could be performed.

Participants

Inclusion criteria were corrected-to-normal vision and no reported history of psychiatric or neurological illness. A convenience sample of 32 healthy participants ($M_{\text{Age}} = 23.56$ years, $SD_{\text{Age}} = 2.78$ years; all but 3 right-handed; 7 male/24 female/1 non-binary) was assessed. None of the participants reported impaired or irregular tactile sensation. Participants were compensated with money or in course credits. All participants provided written informed consent.

Procedure

Prior to participation, participants were instructed to shave their forearm and calf to prevent hair movement that could interfere with any tactile stimulation. Participants provided details of their age, sex, and handedness. We assessed pupil responses to tactile stimulation at each of three body locations: the tip of the right little finger, the right forearm, and the right calf. In addition, we assessed subjective tactile sensitivity for the same three body locations using Von Frey filaments. The order of the pupillometry assessment and the subjective tactile sensitivity assessment was counterbalanced between participants.

Apparatus

Stimuli were presented on an Asus ROG PG278Q monitor (99 Hz, 2560*1440 px, 67.5 cm distance from eye position) in a light- and sound-attenuated room. A chin and forehead rest was used. Psychopy version 2021.2.3 (Peirce et al., 2019) was used to conduct the experiment. Participants' left eyes were tracked using a video-based Eyelink 1000 tracker (SR research; 1000 Hz). A nine-point calibration and validation of the eye-tracker was performed at the beginning of each block.

Tactile stimulation was delivered using custom-made tappers. A tapper consisted of a cord with a copper coil at the end, in which a small magnet and a pin were embedded. Binary input from the PC could reverse the magnetic field, pushing out the magnet and pin. When applied to the skin, this produced a single brief, non-painful tactile stimulation.

Pupillometric assessment

As auditory stimulation causes pupil dilation (Strauch et al., 2020), we ensured that participants could not hear the sound of the tapper. Participants had to wear earplugs and noise-cancelling headphones (Sony WH-1000x M3) playing brown noise. The volume was set to the highest level that the participant found comfortable. To check whether the sound of the tappers was sufficiently masked, a sound detection task was performed. Participants were presented with a grey screen for 1 s, during which a tapper could be fired. Participants then had to indicate whether or not they had heard a tapper by pressing a key, with written instructions presented on the screen after each trial. A tapper would fire in 20 out of 30 trials, in random order. Most participants (n = 11) could not discriminate between tapper-present and tapper-absent trials (d' = 0), one showed limited sensitivity (d' = 0.08), and two showed reversed sensitivity (d' = -0.25 and d' = -1.60).

Adhesive tape was then used to secure the tappers to the tip of the little finger, forearm (positioned in a downward orientation), and calf, ensuring that they were hidden from view (Figure 1A). A foam ring was placed at the base of the little finger to prevent contact with the adjacent ring finger. A fourth tapper was placed on a cushion, to be used in a control condition. The experiment consisted of four blocks, one for each of the three body locations and a control block, which were counterbalanced using a Latin square design. To ensure that the tactile stimulation was similar across locations, the same tapper was always used for the given stimulus location within a block and thus the tapper was swapped between blocks. Each block consisted of 25 trials for the given stimulus location. In addition, every sixth trial, a randomly selected different tapper was fired, to avoid habituation or expectation effects. These trials were not included in the analysis.

The trial sequence is shown in Figure 1B. Throughout the trial, participants had to look at a central fixation cross (white, grey background). Trials started with a variable baseline period of 0.5 to 2.5 s, which was set to 1.5 to 2.5 s after the first 14 participants to ensure a stable baseline pupil measurement. Tactile stimulation was then applied and the pupil response was recorded for a further 1.5 s. Trials were considered invalid if participants blinked or looked >3 visual degrees from the centre for >200 ms. The participant received feedback via a red (invalid) or grey (valid) cross of 0.5 s. After feedback, an intertrial interval of 1.5 s occurred. Invalid trials were repeated at the end of each block. If blinks or gaze deviations from the centre occurred during the baseline, the baseline timer was simply reset to zero and no feedback was given.

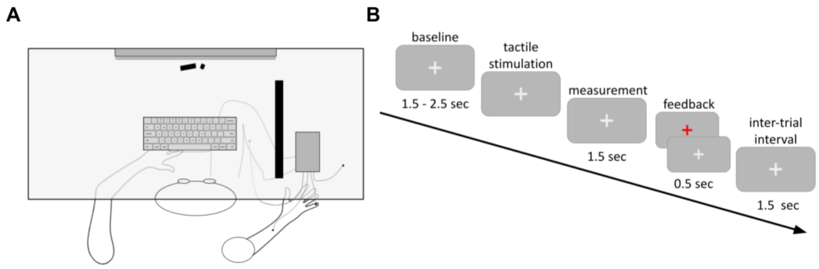

Figure 1. **A)** Schematic representation of the experimental set-up for the tactile stimulation task. Participants were seated at a desk with their head resting on a chin rest. Tappers were attached to the right little finger, arm, and leg. **B)** Trial sequence. Participants had to fixate a central cross. After fixation, the trial started with a baseline period of 0.5 to 2.5 s, followed by the tactile stimulation and a post-stimulus period of 1.5 s. If the participant looked more than 3 visual degrees outside of the centre for more than 200 ms during the measurement period, the trial was invalid. Participants received feedback via a red or grey cross for 0.5 s. The feedback was followed by an intertrial interval of 1.5 s. Invalid trials were repeated at the end of each block.

Subjective tactile sensitivity

For each of the three body locations, i.e., the tip of the little finger, the forearm, and the calf, subjective tactile sensitivity was assessed using Von Frey synthetic monofilaments (North Coast Medical; model: Touch Test) with a force ranging from 0.008 g to 300 g, starting at 2.0 g (Keizer et al., 2012; Weinstein, 1968). Participants were blindfolded and instructed to report whether they felt a stimulus at a given location. The experimenter applied tactile stimulation according to a forced-choice one up/one down staircase procedure (resulting in 5 subthreshold and 5 suprathreshold reversals), pseudo-randomly intermixed with sham trials in which no stimulation was applied. The tactile sensitivity threshold was calculated as the geometric mean of all reversal points, ranging from 0.008 g (high sensitivity) to 300 g (low sensitivity).

Data processing

Python 3.9 scripts were used to process eye-tracking data and statistics (using the statsmodels, scipy.stats, pingouin, and researchpy packages). Data pre-processing for the sound detection task and the subjective tactile sensitivity task was performed in Excel (version 2208).

Pupil size data were subtractively baseline corrected using the average of the last 50 ms of the baseline period and downsampled to 100 Hz. Negative values indicate pupil constriction and positive values indicate pupil dilation.

To minimise the effects of slower frequency trends/drifts in pupil size, the first derivative of pupil size was calculated, indicating the velocity of pupil size changes. Note that the first derivative contains broadly similar information compared to relative pupil size changes (Strauch et al., 2021). The pupil size derivative data were filtered using a low pass Butterworth filter, with a critical frequency of 18 Hz and an order of 3 to remove high frequency noise.

Statistical analyses

All statistical tests were two-tailed with an alpha of 0.05 to determine statistical significance. Non-parametric tests were used for non-normally distributed data. Holm-Bonferroni corrections were used for post-hoc pairwise comparisons.

A linear mixed effects model (LME) was used to examine differences in pupil responses after tactile stimulation of the different body parts and the control condition. The best model was determined by using the Bayesian Information Criterion (BIC), with pupil size derivative as the dependent variable, using random intercepts for each participant. Stimulation site was used as an independent variable (i.e., control condition, little finger, forearm, and calf). The trial number within a block and the block number were additionally included to control for possible habituation effects. It is recommended to fit random slopes for predictor variables unless this leads to non-convergence of the model. As this was the case for several time points, we followed Barr (2013) and only fitted random intercepts.

Next, we tested whether potential differences in the pupil size derivative could be explained by differences in the response latency. The time to the maximum pupil size derivative between the three stimulation sites was compared using Friedman's ANOVA.

To assess whether the three body locations differed in terms of tactile sensitivity, the Von Frey tactile sensitivity threshold was compared between body locations using Friedman's ANOVA.

Data availability

All raw data, materials, analysis scripts, as well as the preregistration can be retrieved via the open Science Framework: https://osf.io/rb3gh/?view_only=2859615bba494f3393b54315fe5aa797.

Results

Figure 2A shows the pupil size as compared to baseline over time, and Figure 2B shows the pupil size derivatives (see Supplementary Figure 1 for plots per participant). First, we found that tactile stimulation at each of the three body locations resulted in larger pupil size derivatives as compared to those in the control condition (see Supplementary Figure 2 for statistical comparisons), demonstrating that the pupil responds to tactile stimulation.

In particular, the pupil showed a faster change in the amount of increase after stimulation of the little finger versus forearm, little finger versus calf, and forearm versus calf. In Figure 2C, the results of the linear mixed effects model are plotted, showing the t -values for comparisons between stimulus locations over time. The results remained conceptually unchanged when simple functional t -tests were performed on the mean traces per condition and participant instead of LMEs (Supplementary Figure 3). Thus, tactile stimulation to the presumably more sensitive body locations resulted in stronger pupil responses as compared to the less sensitive body locations.

The time to the maximum pupil response (Figure 2D) differed between the three stimulation sites, $\chi^2(1596) = 7.76$, $p = 0.021$. The maximum pupil response derivative was later for the calf than for the little finger ($W = 139053$, $p = 0.037$, $r = -0.10$), which was a small effect. There were no differences in the time to maximum derivative between the calf and the forearm ($W = 145287$, $p = 0.200$, $r = -0.06$) and between the forearm and the little finger ($W = 151355$, $p = 0.564$, $r = -0.02$).

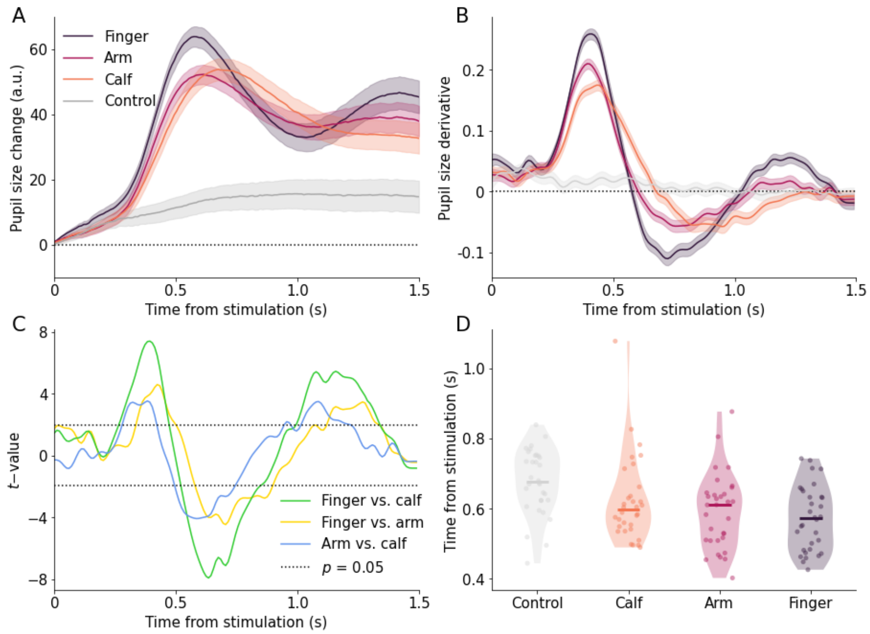

Figure 2. **A)** Baseline-corrected pupil response over time after tactile stimulation, expressed in arbitrary units (a.u.), plotted per stimulation site. Positive values indicate pupil dilation, negative values indicate pupil constriction. Error bands indicate one standard error above and below the mean. **B)** Pupil response derivative traces over time, averaged per stimulation site. Positive values indicate the change in the amount of pupil size increase, negative values indicate the change in the amount of pupil size decrease compared to the previous time point. Error bands indicate one standard error above and below the mean. **C)** Linear mixed effects model for pupil response comparing t -values between stimulus locations over time in seconds. Each line represents the t -values of the comparisons between stimulus locations on pupil response after tactile stimulation over time, with an additive effect of block number and trial number within a block and random intercepts for each participant. The dotted line represents $t = |1.96|$, corresponding to $p = 0.05$. **D)** Time to maximum pupil response in seconds, averaged per participant and split between stimulation sites.

Tactile sensitivity thresholds as assessed with the Von Frey filaments (see Supplementary Figure 4 for the thresholds per location) differed between the three body locations, χ^2 (62) = 44.43, $p < 0.001$. Lower subjective tactile sensitivity thresholds were observed for the little finger versus forearm ($W = 1$, $p <$ 0.001, $r =$ -0.86), little finger versus calf ($W = 1$, $p < 0.001$, $r =$ -0.87), and forearm versus calf ($W = 65$, $p < 0.001$, $r =$ -0.66), all with large effect sizes.

As an exploratory analysis, for each of the pairs of body locations, we examined whether the difference in tactile sensitivity thresholds (as assessed with the Von Frey filaments) was related to the difference in pupil response. In other words, did the decrease in subjective tactile sensitivity thresholds across body locations scale with the increase in the strength of pupil responses in response to tactile stimulation? For each pair of body locations (i.e., finger-calf, finger-forearm, forearm-calf) we calculated difference scores for tactile sensitivity thresholds and for pupil responses over time. These difference scores were correlated using Spearman correlations, shown in Figure 3A, together with functional p -values, shown in Figure 3B. Differences in Von Frey tactile sensitivity thresholds and pupil derivative were positively correlated for the finger versus calf, and for the arm versus calf, at approximately 0.5 to 0.7 s after stimulation, but not for the finger versus arm. Although correlations for $n = 32$ must be interpreted with caution, this suggests at least tentative support for the idea that the here proposed pupillometric estimate and Von-Frey filaments measure similar or related latent tactile processing.

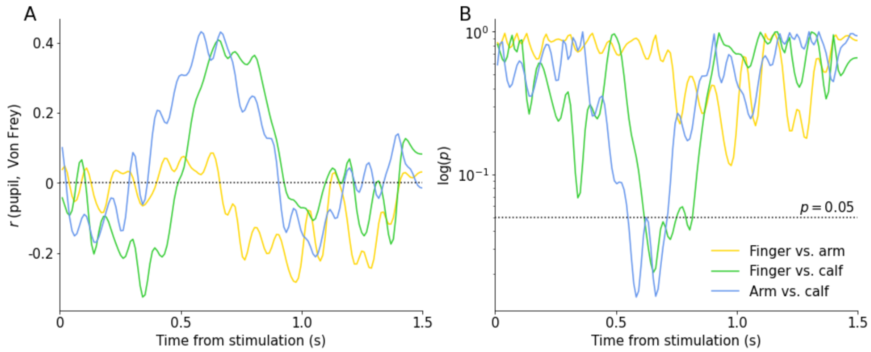

Figure 3. A) Correlation between differences in the first derivative of pupil size changes and Von Frey tactile sensitivity thresholds between body locations over time. **B)** Functional uncorrected significance tests for these correlations. The$p$ -values are log-transformed, the ticks on the y-axis indicate the respective steps. Both correlations between the finger and calf, and the arm and calf reached statistical significance after about 0.5 to 0.6 s and lasted up to 0.7 s.

Interim discussion

As hypothesised, tactile stimulation elicited pupil dilation responses that could not be attributed to visual or auditory input. In particular, we observed more pronounced pupil dilation following tactile stimulation of body locations with a presumed higher tactile sensitivity. Specifically, stronger responses were observed for the little finger versus calf, the little finger versus forearm, and the forearm versus calf. A slower pupil response to tactile stimulation of the calf compared to the finger could partly contribute to the differences in pupil response strength between these body locations. However, no differences were found in the latency of the pupil response between the forearm and the finger. The presumed difference in subjective tactile sensitivity between the finger, the arm, and the calf was replicated using a tactile detection paradigm with Von Frey filaments and showed superior tactile detection abilities for the little finger versus calf, the little finger versus forearm, and the forearm versus calf, consistent with existing work (Weinstein, 1968). A tentative direct relationship was observed between the differences in pupil responses between pairs of stimulated body locations (although not for the finger versus arm comparison), and the differences in tactile sensitivity between the same pairs. However, these relationships must be interpreted with caution due to the relatively small sample size for the correlative analyses. In conclusion, our results show that tactile stimulation applied to different parts of the body elicits pupil responses of varying magnitude, probably due to differences in tactile sensitivity. In Experiment 2, we investigated whether pupil responses following tactile stimulation at a single body location would scale with stimulus intensity, expecting stronger pupil responses with more intense stimulation as shown in less controlled previous work (van Hooijdonk et al., 2019).

Experiment 2

Methods and statistical analyses were as in Experiment 1, unless otherwise stated.

Materials and methods

The research and consent procedures were approved by the Ethics Committee of the Faculty of Social and Behavioural Sciences of Utrecht University (protocol number 23-1738). Participants were recruited between June and July 2023. No power estimation was performed.

Participants

A convenience sample of 20 healthy participants ($M_{\text{Age}} = 24.55$ years,$SD_{\text{Age}} = 2.87$ years; all but one right-handed; 6 male/14 female) was included, of whom one of the authors (IH).

Procedure

We assessed pupil responses to tactile stimulation of three different intensities (i.e., low, medium, high) applied to the tip of the right little finger. We then assessed participants' ability to discriminate between the different stimulation intensities.

Apparatus

Tactile stimulation was delivered using a tactor (Dancer Design), a miniature electromagnetic solenoid type stimulator. The tactor provided vibrotactile stimulation at 40 Hz. Four different levels of stimulation intensity were provided: 0%, 20%, 50%, and 100%. Stimulus intensity was treated as an ordinal variable (i.e., 20%: low intensity, 50%: medium intensity, 100%: high intensity) because no information on absolute intensities was available. The intensity of the vibrotactile stimuli is exponentially related to the perceived intensity of the vibrotactile stimuli (Stevens, 1959), so we chose for larger percentage differences between medium and high intensities than between low and medium intensities. Participants had to wear earplugs to ensure that they did not hear the sound produced by the tactor. As the tactors produced almost no sound, neither sound detection control task, nor additional headphones were considered necessary.

Pupillometric assessment

Adhesive tape was used to attach the tactor to the tip of the right little finger, which was hidden from view. A foam ring was placed at the base of the little finger to prevent it from touching the adjacent ring finger.

The experiment consisted of 50 trials per stimulus intensity (i.e., none, low, medium, high), resulting in 200 trials in total. Stimulus intensities were randomised within clusters of 20 trials, to ensure a balanced presentation. The trial sequence was similar to that in Experiment 1, except that the tactile stimulation lasted for 80 ms and the pupil response was recorded for 1.58 s after stimulus onset.

Tactile discrimination

We assessed whether participants could discriminate between the different stimulus intensities. In each trial, vibrotactile stimuli of two different stimulus intensities were presented to the right fingertip for 80 ms each, separated by a 1 s pause. Participants then had to indicate whether they perceived the first or second vibration to be stronger by pressing either '1' or '2' on a keyboard, and how confident they were in this choice by providing a certainty score on a scale ranging from 0 (not at all sure) to 100 (completely sure), by providing a mouse click. There were five trials per unique stimulus pair and order, resulting in a total of 30 randomly presented trials.

Data processing

Data pre-processing for the tactile discrimination was performed in Excel (version 2208).

Statistical analyses

The four stimulus intensities (i.e., none, low, medium, high) were included as predictors of pupil size in a linear mixed effects model. The trial number was also included to control for possible habituation effects.

As in Experiment 1, the time to the maximum pupil size derivative was compared between the four stimulus intensities.

To assess whether participants could discriminate the different stimulus intensities within each pair, we tested whether the number of correct responses was above chance level (i.e., 5 out of 10 correct responses) using parametric one-sample t -tests or non-parametric Wilcoxon signed rank tests. Next, we compared the performance (i.e., number of correct responses) and participants' confidence in their responses between the three pairs of stimulus intensities using a non-parametric Friedman's ANOVA and post-hoc Wilcoxon signed-rank tests. One participant had no data available on the discrimination task and was excluded from these analyses.

Results

Figure 4A shows the changes in pupil size relative to baseline over time, Figure 4B shows the pupil size derivatives (see Supplementary Figure 5 for plots per participant). First, we found that tactile stimulation at each of the three stimulation intensities resulted in larger pupil size derivatives as compared to the no-stimulation condition (see Supplementary Figure 6 for the statistical comparisons), replicating the stimulation effect reported in Experiment 1.

We found faster increases in pupil size following high versus low intensity tactile stimulation, and medium versus low intensity tactile stimulation. No difference was found between high and medium intensity stimulation. In Figure 4C, the results of the linear mixed effects model are plotted, showing the t -values for comparisons between stimulus intensities over time. The results remained conceptually unchanged when simple functional t -tests were performed on the mean traces per condition and participant (Supplementary Figure 7). Thus, tactile stimulation at higher stimulus intensities resulted in larger pupil responses as compared to lower stimulus intensities.

The time to maximum pupil response (Figure 4D) did not differ between the three stimulus intensities, $\chi^2(1998) = 0.58, p = 0.748$, indicating that differences in pupil response after tactile stimulation were not driven by differences in pupil response latency.

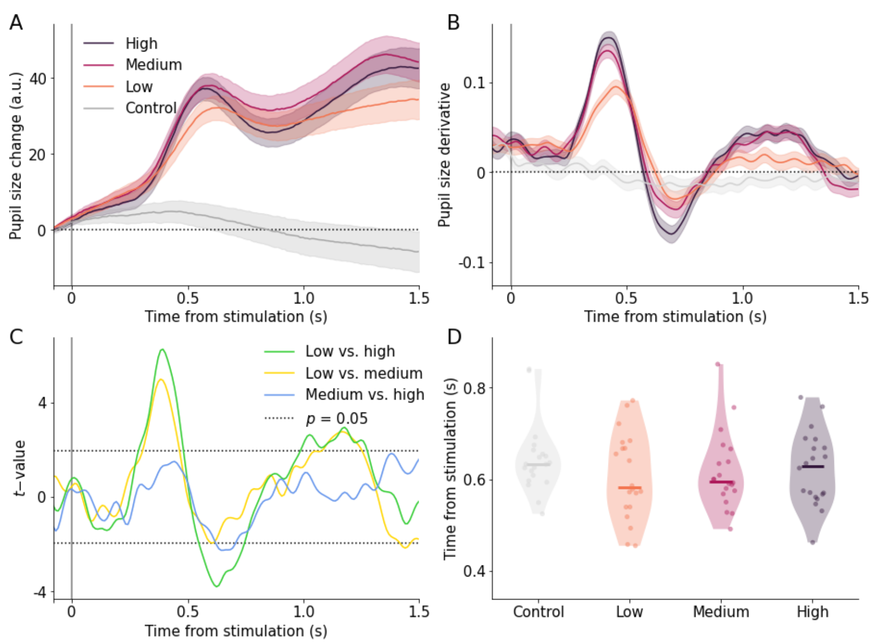

Figure 4. A) Baseline-corrected pupil response over time after tactile stimulation, expressed in arbitrary units (a.u.), plotted per stimulation intensity. Positive values indicate pupil dilation, negative values indicate pupil constriction. Error bands indicate one standard error above and below the mean. **B)** Pupil response derivative traces over time, averaged per stimulation intensity. Positive values indicate the change in the amount of pupil size increase, negative values the change in the amount of pupil size decrease compared to the previous time point. Error bands indicate one standard error above and below the mean. **C)** Linear

mixed effects model for pupil response comparing t -values between stimulation intensities over time in seconds. Each line represents the t -values of the comparisons between stimulation intensities on pupil response after tactile stimulation over time, with an additive effect of trial number and random intercepts for each participant. The dotted line represents $t = |1.96|$, corresponding to $p = 0.05$. **D)** Time to maximum pupil response in seconds, averaged per participant and split between stimulation intensities.

Participants performed above chance level in the forced-choice task discriminating between the three stimulus intensities (low vs. medium: $W = 0$, $p < 0.001$, $r = 0.51$; low vs. high: $W = 1$, $p < 0.001$, $r = 0.92$; medium vs. high: $t(18) = 5.22$, $p < 0.001$, $d = 3.92$; see Supplementary Figure 8A for performance per stimulus intensity pair). Performance differed between the three stimulus intensity pairs, $\chi^2(38) = 26.63$, $p < 0.001$. Participants performed worse in discriminating the medium vs. high intensities as compared to the low vs. high intensities ($W = 0$, $p = 0.002$, $r = -0.82$), and as compared to the low vs. medium intensities ($W = 0$, $p = 0.001$, $r = -0.85$), both with large effect sizes. No differences were found between the low vs. medium intensities as compared to the low vs. high intensities ($W = 6$, $p = 0.655$, $r = -0.10$). Thus, participants were better able to discriminate the low intensity from the medium and high intensities; whereas the medium and high intensities were perceived as being more similar.

Participants differed in the certainty of their responses in the stimulus intensity discrimination task, $\chi^2(38) = 25.62$, $p < 0.001$ (see Supplementary Figure 8B for the certainty scores per stimulus intensity pair). Participants were less confident discriminating the medium vs. high intensities as compared to the low vs. high intensities ($W = 5$, $p < 0.001$, $r = 0.83$), and as compared to the low vs. medium intensities ($W = 1$, $p < 0.001$, $r = 0.87$), both with large effect sizes. There were no differences between the low and medium intensities as compared to the low and high intensities ($W = 44$, $p = 0.124$, $r = 0.38$). Thus, the certainty scores were consistent with the accuracy in discriminating the different stimulus intensities.

As an exploratory analysis, we examined whether the ability to discriminate between the medium and high stimulus intensities, and the certainty of this judgement, were correlated with the difference in pupil size response to tactile stimulation at medium and high stimulus intensities. Only the effect for the medium vs. high stimulus intensity was evaluated, as participants showed the most variation in their discriminative performance for this stimulus pair.

We calculated difference scores for the discriminability and certainty scores for tactile stimulation of the medium vs. high stimulus intensity and for pupil responses over time. These difference scores were correlated using Spearman correlations. No consistent correlations between differences were observed over time (see Supplementary Figure 9 for details).

Discussion

Previous studies of the perceived intensity of tactile stimuli have relied on overt motor or verbal responses. However, a more objective measure of perceived tactile intensity has so far been lacking. Such an index is useful when overt responses are not possible or to avoid explicit bias. Furthermore, it is crucial to tear apart the objective components of touch processing from subjective reports. Here, we set out to systematically test pupil size change as an objective measure of perceived intensity of tactile stimulation. We found greater pupil dilation following stimulation of constant intensity on more sensitive parts of the body (Experiment 1) and following higher stimulation intensity on the finger (Experiment 2). This highlights the usefulness of pupillometry as a means of studying tactile perception.

Present findings and theoretical contributions

In the current study, pupils responded more strongly to tactile stimulation of more sensitive parts of the body. Specifically, stronger pupil responses were observed after stimulation of the little finger versus calf, the little finger versus forearm, and the forearm versus calf. Secondly, pupils responded more strongly to more intense vibratory stimulation on the finger as compared to less intense vibratory stimulation. In both experiments, the enhanced response was reflected in a greater increase in pupil size already within 0.5s of stimulation, providing the basis for short measurement times and therefore minimal effort on the part of the participant (to maintain fixation), as there is sufficient time between trials for the pupil size to return to baseline. Our results align with previous findings from less systematic and less controlled studies, in which greater pupil dilations were observed in response to more intense thermal stimulation (Drummond & Clark, 2023; Eisenach et al., 2017) and faster stroke velocity (van Hooijdonk et al., 2019).

The greater increase in pupil size in response to stimulation of more sensitive body parts or more intense stimulation is likely due to more intense cognitive processing associated with greater noradrenaline release (Alnaes et al., 2014; Aston-Jones & Cohen, 2005; Joshi et al., 2016; Murphy et al., 2014; Strauch et al., 2022), which has been interpreted to subserve the communication between neural populations (Dahl et al., 2022; Wainstein et al., 2022).

It is important to note that overt responses to tactile stimulation may not solely reflect the objective intensity of the brain's processing of tactile stimulation, but also less tangible aspects such as interoception and response biases. The here proposed method allows for a more refined approach to disentangling these components and studying where they align or diverge, respectively. The fact that our pupil-based assessment of tactile processing intensity showed moderate correlations with subjective indicators of tactile perception for Experiment 1, but not Experiment 2 may be seen as a first pointer that the here indexed processing intensity does not necessarily always reflect overt responses.

A roadmap to solve outstanding questions and challenges

Using more standardized pupillometric setups, such as the one introduced in this study, opens up exciting possibilities. Pupil responses to touch can be used to investigate at which level tactile stimulation is processed. For instance, if tactile stimuli elicit a pupil response without explicit conscious perception, it implies that the stimulus is only implicitly processed, a dissociation that resembles a condition termed numbsense (Gallace & Spence, 2008; Rossetti et al., 1995). To gain further insight into the patterns of pupil response for consciously and unconsciously perceived stimuli, measuring pupil responses after tactile stimulation on numbed skin using local anesthesia could be employed. While it has been shown that pupil responses scale with the intensity of nociceptive stimuli (Chapman et al., 1999; Sabourdin et al., 2018; Wildemeersch et al., 2018) and with the concentration of administered analgesia (Aissou et al., 2012; Larson et al., 1997), there is a gap in understanding pupil response after non-noxious tactile stimulation on a body location under local anesthesia. Alternatively, paradigms could be used in which the stimuli are presented at the threshold of detection (Gusso et al., 2022) or in which attention for the stimulated location is manipulated. The resulting findings could contribute to a better understanding of (subtypes of) tactile hypo- and hypersensitivity in pathologies such as chronic pain (fibromyalgia, complex regional pain syndrome) and autism spectrum disorder, and neuropsychological disorders such as tactile neglect and extinction following brain damage. Potentially, characteristics of the pupil response following tactile stimulation may be used to index the level of (residual) processing of touch, and consequently predict recovery or outcomes of rehabilitation therapy.

The differences observed in pupil responses across the three stimulated body locations in our study were in line with the known patterns of subjective tactile sensitivity (Weinstein, 1968). The pupillometric index could be used to expand these findings and create a "pupil-based homunculus" – where pupil responses serve as a detailed map, mirroring the processing intensity of tactile sensation in the brain. This could potentially lead to novel insights on the underlying neural mechanisms of differences in tactile sensitivity of different body parts. Whilst our results show clear evidence of stronger pupil dilation to stimulation to more subjectively sensitive body parts and stronger stimulation, at this point, we cannot elucidate which mechanical receptor types drove these effects the strongest. However, the systematic variation of stimulation frequency at constant amplitude might allow to narrow down this question, as different types of mechanoreceptors have different frequency ranges to which they are most sensitive (Delhaye et al., 2018). For instance, Meissner's Corpuscles reportedly respond strongest to stimulation in the band of 10 to 50 Hz (Piccinin, MA, Miao, JH, Schwartz, 2022), whilst Pacinian Corpuscles should respond stronger to stimulation at much higher frequencies such as 250 Hz (Talbot et al., 1968). A straightforward prediction is therefore that matching stimulation intensities trigger certain receptor types specifically. Comparing pupil responses to these different frequencies at constant amplitude could therefore allow to make inferences about relative receptor distributions/proportions.

While the current method effectively shows the predicted differences between conditions at a group level, substantial individual variability poses a challenge. To enhance the method for both research and clinical use, it is crucial to optimize the signal-to-noise ratio, and obtain a measure that ideally encompasses a low number of trials and is still reliable.

Conclusion

We set out to test pupillometry as an objective indicator of touch processing. In a first experiment, we showed that the pupil responded differently following tactile stimulation at the finger, arm, and calf. More specifically, the pupil responded more strongly following stimulation of more sensitive body locations. In a second experiment, we found that the pupil responded more strongly to vibrotactile stimulation of higher intensities applied at the finger. Altogether, these findings show that pupil responses have the potential to be used as an objective index of tactile sensitivity that is not dependent on verbal responses.

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Author contributions

A.F. Ten Brink, C. Strauch, and H.C. Dijkerman conceptualized the studies. A.F. Ten Brink, I. Heiner, and C. Strauch contributed to the study design under assistance of H.C. Dijkerman. Implementation and data curation were performed by I. Heiner under supervision of A.F. Ten Brink and C. Strauch. I. Heiner and C. Strauch performed the data analysis and visualization of results, under assistance of A.F. Ten Brink. A.F. Ten Brink, I. Heiner, and C. Strauch wrote the draft of the manuscript. A.F. Ten Brink, I. Heiner, H.C. Dijkerman, and C. Strauch provided critical review & editing.

Conflict of interest

Declarations of interest: none.

Supplementary material and data, inclusion/exclusion

Supplementary material and data can be found online via https://osf.io/rb3gh/?view_only=2859615bba494f3393b54315fe5aa797. We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study

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