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RESEARCH ARTICLE

# Tactile localization depends on stimulus intensity

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**Abstract** Few experimental data are available about the influence of stimulus intensity on localization of cutaneous stimuli. The localization behavior of an individual as function of the veridical stimulus sites can be represented in the form of a perceptual map. It is unknown how the intensity of cutaneous stimuli influences these perceptual maps. We investigated the effect of stimulus intensity on trial-to-trial localization variability and on perceptual maps. We applied non-painful electrocutaneous stimuli of three different intensities through seven surface electrodes on the lower arm of healthy participants. They localized the stimuli on a tablet monitor mounted directly above their arm, on which a photograph of this arm was presented. The length of the arm over which the stimuli were localized was contracted when compared to the real electrode positions. This length increased toward veridical with increasing stimulus intensity. The trial-to-trial variance of the localizations dropped significantly with increasing intensity. Furthermore, localization biases of individual stimulus positions were shown to decrease with increasing stimulus intensity. We conclude that tactile stimuli are localized closer to veridical with increasing intensity in two respects: the localizations become more consistent and more accurate.

**Keywords** Perceptual map · Localization · Intensity · Influence of intensity on localization · Electrocutaneous stimulation · Body representations

## Introduction

Various studies have demonstrated the localization of cutaneous stimuli to systematically deviate from the veridical stimulus locations (Pillsbury 1895; Franz 1916; Culver 1970; Trojan et al. 2006, 2010; Mancini et al. 2011). These biases can be represented in the form of a perceptual map, which describes the localizations as a function of the veridical stimulus positions (Trojan et al. 2006). In a previous publication, we argued that somatosensory perceptual maps reflect the properties of body representations (Steenbergen et al. 2013). This may be especially useful in studying pathologies that have been demonstrated or suggested to go hand in hand with distorted spatial perception, such as complex regional pain syndrome (Moseley et al. 2009; Reinersmann et al. 2012), fixed dystonia (Edwards et al. 2011), and eating disorders (Urgesi et al. 2011). Before using perceptual maps to study patients, it would be useful to gather information about what constitutes a "normal" perceptual map. This includes the dependence of perceptual maps on various stimulus parameters, such as stimulus intensity.

The influence of stimulus intensity on localization of cutaneous stimuli has not been studied systematically. While Franz (1913) reviews findings by Ponzo (1911)

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that trial-to-trial variance of tactile localization is reduced with increasing mechanical pressure, he himself was unable to replicate these findings. Neither Ponzo nor Franz found convincing effects of stimulus pressure on localization biases. Both studies included only two participants. Hamburger (1980) found a decrease in absolute localization error with increasing stimulus pressure in a population of five participants, but did not discriminate between the effects of trial-to-trial variance and systematic mislocalizations. The contradictory and anecdotal nature of these results does not give a clear picture of the effect of stimulus intensity on cutaneous localization. This topic therefore requires investigation, especially since we identified stimulus intensity as a possible confounder in a previous study in which we compared perceptual maps of tactile and nociceptive stimuli (Steenbergen et al. 2012a).

In peripheral nerve fibers, stimulus intensity is coded by the firing frequency and the number of active nerve fibers (Bensmaia 2008). When activating these nerve fibers using electrical stimulation, firing frequency coding can be exploited using pulse train modulation (PT), which is stimulating with a pulse train consisting of a varying number of pulses (NoP) of constant amplitude (van der Heide et al. 2009). In general, when using electric stimulation of cutaneous nerve fibers, selectivity for a certain fiber population cannot be guaranteed, with the notable exception of needle electrodes with low stimulus currents (Mouraux et al. 2010; Inui and Kakigi 2012). Because in PT the stimulus current is constant for all intensity levels, the activated fibers are the same for each stimulus level and consequently so are the proportions of different fiber types that are activated.

Modifying stimulus intensity by varying the pressure of a mechanical stimulus has two simultaneous effects: it leads to a change in activity in the recruited sensory fibers, but it also varies the skin area over which fibers are activated (Kandel et al. 2000). Because of this, the effect of mechanical stimulus intensity cannot be extricated from the change in spatial extent of the stimulus. Since electric stimulation with PT only influences the activity in a constant fiber population, it is particularly suitable for studying the effect of stimulus intensity alone.

In the current paper, we present a study on the effect of stimulus intensity on localization of cutaneous stimuli. In a series of experiments, we used electrical stimulation through surface electrodes on the lower arm to elicit non-painful sensations with three levels of intensity. The intensity of the stimuli was varied using pulse train modulation. Participants repeatedly reported the location of these stimuli at seven sites using a pointing task. Two aspects of the localization data were investigated. Based on the theory outlined above, we expected the trial-to-trial standard deviations of the localizations to drop with increasing stimulus intensity. Concerning the effect of intensity on the perceptual maps, localizations may rely more on the general location of the arm for weak stimuli. Therefore, we hypothesized that weaker stimuli are reported more toward the center of the arm.

## Methods

### Participants

Fifteen participants were recruited from the student and employee population of the University of Twente. All participants gave written informed consent prior to the experiments. The participants were aged 24 ± 3 years (mean, M ± standard deviation, SD, range 18–29 years); seven participants were female; one participant was left-handed. The arm lengths measured from the wrist to the skin fold of the arm joint were 23 ± 2 cm. The protocol was approved by the Medical Ethical Board Twente (file number NL35875.044.11).

### Electrocutaneous stimuli

The stimuli were applied using an eight-channel stimulator similar to the ones used in previous studies of our group (van der Heide et al. 2009; Roosink et al. 2011; Steenbergen et al. 2012b, 2013).

The stimuli for the localization experiments were applied through surface electrodes, which were placed on the dorsal lower arm. Previous studies have shown these stimuli to result in a mostly tactile sensation (Steenbergen et al. 2012b). When participants are asked to rate these stimuli on a quality scale ranging from dull to sharp, they are rated as dull compared to nociceptive stimuli (Steenbergen et al. 2012b, 2013). Because we wanted to assess whether the stimuli in the current experiment resulted in the same quality of perception, we needed a nociceptive reference stimulus, which was provided by needle electrodes that were placed at one site on the arm. This general setup with seven surface electrodes and one needle electrode site was realized using two different sets of electrodes as described below. The reason for this difference in setup was that after performing the first five experiments, evaluation of the reported stimulus qualities (obtained using the procedure described below) revealed different results than expected based on the previous work. We therefore changed to a different setup. However, as we will show, the change in electrodes did not affect this scoring behavior notably, and for that reason, we decided to pool the first five participants with later participants.

In the first five participants, Ambu “blue sensor BRS” cardiology electrodes were used, which are rectangular in shape and 1.5 by 2 cm in size. These were placed on the

dorsal lower arm and were spaced equidistantly between 20 and 80 % of the length between elbow and wrist; this is the same method we used before (Steenbergen et al. 2013). Stimuli through these electrodes are generally reported as dull in comparison with nociceptive electrocutaneous stimuli through needle electrodes, which are mostly perceived as a pricking or tingling sensation (Steenbergen et al. 2013). In addition to the seven Ambu electrodes, a single needle intra-epidermal stimulation (IES) electrode was placed at the wrist (Inui and Kakigi 2012).

In the remaining ten participants, compound electrodes were used, which are capable of independently eliciting tactile and nociceptive sensations (Steenbergen et al. 2012b). Each of these devices consists of four disc electrodes and five needle electrodes. The discs elicit sensations comparable to the Ambu electrodes, while the latter are comparable to IES electrodes. The devices were spread out over the full length of the dorsal lower arm (between 0 and 100 % of the elbow–wrist distance) and placed independently of each other. Instead of the IES electrode as used in the first five participants, the needle electrodes of the middle compound electrode were used. The needle electrodes at the other sites were not used.

For all participants, a reference electrode (a Protens 9 × 5 cm rectangular TENS electrode) was placed on the dorsal hand. All electric stimuli were cathodic pulses with a pulsewidth 0.21 ms.

During the experiment, the perceived stimulus intensity was modified by applying stimuli with a varying number of pulses (NoP). The levels were NoP = 1, NoP = 3, and NoP = 7; an unequal increase in NoP was used because the effect of increasing NoP on perceived stimulus intensity levels off for higher NoP (van der Heide et al. 2009). The time between pulse onsets was 5 ms. The stimulus current for each stimulus electrode was 120 % of the sensation threshold of that electrode.

## Procedure

Before the electrodes were placed, the participants were seated and they put their bare non-dominant arm in an arm holder. A photograph was taken of the arm in the holder from the perspective of the participant. Following this, the participants' view of their arm was obstructed by a tablet monitor (Provision Visboard VA122B, with a 22-inch diameter and a resolution of 34.15 pixels/cm), and the electrodes were attached. Next, the tablet monitor was placed as close as possible to the arm, and the photograph of the arm without electrodes was displayed. The photograph was scaled such that the participants reported their view of the displayed arm to match that of their real arm. This was followed by three experimental procedures: sensation threshold determination, assessment of stimulus qualities and intensities, and the actual localization experiment. After the localization experiment, a photograph was taken of the arm with electrodes. Participants were instructed to move their arm as little as possible, but were allowed to make small movements if they were uncomfortable.

### *Sensation thresholds*

The sensation threshold was determined for each electrode in each participant. The threshold was defined as the amplitude for which a single pulse stimulus had a 50 % chance of detection. This amplitude was determined using an adaptive staircase procedure as described in Steenbergen et al. (2012b).

### *Quality and intensity assessment*

Next, the perceived quality and intensity of the stimuli to be used for the localization experiment were assessed using quality and intensity visual analog scales, VAS (Steenbergen et al. (2012b), see Fig. 1). These scales allow participants to report the perceived intensity and quality of stimuli, which are then converted to numbers between 0 and 10. These extreme values are labeled *no sensation* and *strongest sensation imaginable* for the intensity scale and *dull* and *sharp* for the quality scale.

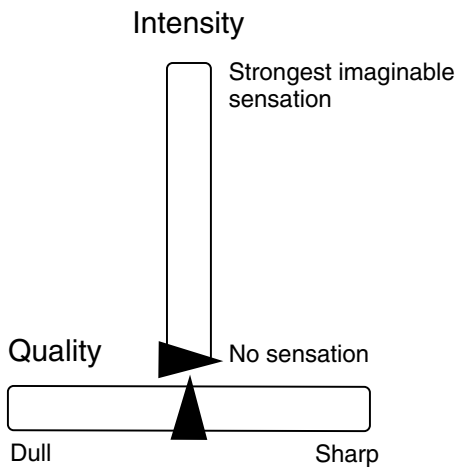



**Fig. 1** Quality and intensity assessment scales as presented in Steenbergen et al. (2012b). The perceived intensity of a stimulus can be reported using the vertical intensity scale, which ranges from "no sensation" to "strongest sensation imaginable." After reporting, the rating is stored as number between 0 ("no sensation") and 10 ("strongest sensation imaginable"). The perceived quality is reported on the horizontal quality scale, which ranges from "dull" to "sharp." These scores are stored as a number between 0 ("dull") and 10 ("sharp"). By comparing the VAS scale results with label assignments, we demonstrated that the dull half of the scale is associated with tactile sensations and the sharp half with nociceptive sensations. Before each scoring of a stimulus, the scales are preset as shown above, which corresponds to an intensity score of 0 and quality score of 5

The aim of this procedure was to make sure that all stimuli during the subsequent localization experiment were perceived as dull compared with needle electrode stimuli. If only stimuli through the seven surface electrodes would be applied during the VAS scoring procedure, there is a chance that all of them would be perceived as tactile, which would make it hard for participants to make quality judgments. For this reason, nociceptive stimuli were included in the procedure. These were applied either through the IES electrode at the wrist (for the five participants equipped with the Ambu electrodes) or through the needle electrodes of the middle compound stimulus device (for the other ten participants). Each stimulus level (NoP = 1, 3, and 7) was applied four times at each site. The stimulus order was block randomized for each participant, with each block containing all stimulus conditions in a random order. If participants reported sharp sensations for the surface electrodes (quality scores higher than 5.00), this was interpreted as a sign of nociceptive co-activation and the stimulus currents (for the five participants with Ambu electrodes) or electrode placement (for the other ten participants) was changed for the relevant electrode(s). If electrodes were moved to another site, the sensation threshold for this electrode was determined again. After this, the quality and intensity assessment procedure was repeated. Following this, the localization procedure was performed.

The final stimulus currents of the surface electrodes for the localization experiment were 3.28 ± 1.19 (M ± SD) mA. The stimulus currents of the IES electrodes, which were only used during the quality–intensity assessment, were 0.63 ± 0.34 mA for the first five participants (who were fitted with an Inui IES electrode) and 1.21 ± 0.61 mA for the other ten (who were stimulated through the needles of one of the compound electrodes).

*Localization experiment*

Participants localized the stimuli with their dominant hand by tapping with a pen on a photograph of their own arm, which was presented on the tablet screen overlaying the stimulated arm. For this procedure, the needle electrodes were not used. Each of the 21 different stimulus conditions (seven sites times three intensity levels) was applied 20 times. The amplitude settings of the final run of the quality/intensity assessment were used. The stimuli were randomized in blocks, each of which contained all 21 stimuli. A different stimulus sequence was generated for each participant. At two points during the experiment, after 147 and 294 stimuli, the experiment was halted for a few minutes to allow the participants to rest. The median duration of the localization procedure was 78 min, ranging from 57 to 125 min.

Analysis

All data preparation was performed in MATLAB (version 7.13.0. Natick, Massachusetts: The MathWorks Inc., 2011).

The four intensity and quality scores of the final run of the quality and intensity assessment for each electrode site and stimulus level were averaged, resulting in 21 scores for each participant.

The raw localization data were acquired as *x*–*y* coordinates in pixels, this was reduced to a single dimension by projecting them orthogonally on an axis oriented along the arm. After this, outliers were detected separately for each of the 21 conditions in each participant and excluded from further analysis. Outliers of each condition in a participant were defined as being 1.5 times the interquartile distance removed from the median localization of that condition in that participant. In total, 105 of 7,200 trials were removed from the dataset in this way.

The electrode sites were extracted in the same coordinate frame as the localizations by scaling a photograph of each participants' arm with electrodes to the arm without electrodes as it was presented on the tablet screen. Following this, the electrode sites of each participant were projected to the same axis as was used for the data of that participant.

Finally, the localization data and electrode sites were normalized to the arm length, with 0 being the elbow and 1 the wrist. For these calculations, the location of the outermost electrodes was used as reference. For the Ambu electrode setup, these were located at 0.2 and 0.8 times the arm length, for the compound electrode setup this was 0 and 1.

From the localization data, we calculated the standard deviations (SD) and mean error of localization for each condition in each participant. The mean errors of localization were calculated as absolute distance between the mean localization of an electrode and its veridical location. Participants 8 and 9 did not perceive any sensation for some of the conditions during the quality and intensity scoring procedure (15 out of 315 cases in total). During the localization procedure, participant 6 did not detect stimuli for one additional condition, leading to a total of 16 missing cases for the absolute errors of localization. For the SDs, we excluded conditions for which the SD was calculated from less than 10 localization trials, leading to a total of 29 missing cases for the SD data.

*Analysis of quality and intensity scores*

A repeated measures analysis was performed on the participant and site-averaged intensity and quality scores. The intensity scores were log transformed before analysis to correct for skewness. The analysis was performed using the linear mixed model (LMM) of PASW (SPSS

18.0, Chicago, Illinois: IBM SPSS Inc., 2009). The dataset had missing data; LMMs have the advantage that they can analyze data with missing cases without excluding participants with missing data as is the case in the General Linear Model. Fixed effects for *Site*, NoP, and *Site* × NoP were modeled as repeated factors with diagonal covariance structure for the residuals. In addition, a random intercept for participants was added. The results from this analysis can be interpreted in the same way as a repeated measures ANOVA obtained through the General Linear Model procedure.

*Analysis of the perceptual maps*

Group-level perceptual maps were analyzed by fitting an LMM on all data trials in PASW 18. To test for a main effect of the different stimulus levels, NoP was modeled as a fixed categorical effect (three levels: NoP = 1, NoP = 3, and NoP = 7). The slope was modeled by adding *Stimulus site* as fraction of the arm length (continuous, ranging from 0 to 1) as fixed covariate as well as its interaction with NoP. This interaction resulted in a separate slope estimate for each level of NoP. To correct for a possible drift of the localizations over time, *Repetition* of each stimulus condition (integer, ranging from 1 to 20) was modeled as covariate, as was its interaction with NoP. Because we wanted to test whether the slope for *Stimulus site* changed in the course of the experiment, an interaction between *Repetition* and *Stimulus site* was added as well. Random effects were added for intercept, *Stimulus site* and *Repetition*. The random intercept accounted for differences in intercept between participants. The random slopes for *Stimulus site* and *Repetition* accounted for possible differences in perceptual maps and drift over time between participants. To prevent different numbers of included trials between participants and sites from causing unequal influence of different stimulus sites on the fitted model, a weighting factor of one divided by the number of included trials for each NoP × *Site* × *Participant* condition was applied.

*Standard deviations and localization errors*

The effect of NoP on the localization SDs was tested by fitting a repeated measures LMM on the standard deviation data containing the same fixed and random effects as the quality and intensity score analyses. To estimate whether differences in stimulus quality could be a confounder in this study, a between-subjects factor was added, which identified the sites with high-quality scores from sites with low-quality scores. This was done separately for each of the seven stimulus sites. The median quality score for a site was calculated, and the participants were split into a high- and a low-quality group for that site based on this median. The resulting factor, named *High-/low-quality score*, was added to the LMM as well as its interaction with NoP.

Because of the exclusion of SDs calculated from less than 10 localization trials, the dataset had missing data.

The absolute errors were analyzed using Friedman tests in MATLAB. The factor for this analysis was NoP, for the nuisance factor all sites and participants were pooled. Any of the 105 site-by-subject entries for which one or more of the NoP levels had missing data were removed from analysis. To investigate whether stimulus quality influenced the absolute errors, the absolute errors of the sites that received a high-quality and low-quality score (see above) were compared for each of the three stimulus levels using three Wilcoxon rank sum tests.

## Results

Quality and intensity scores

Figure 2a shows the reported intensity scores for all participants, sites, and NoP. On average, pulse train modulation influenced the reported stimulus intensity, with a higher intensity being reported for increasing NoP (significant, see the LMM repeated measures results presented in Table 1). No significant main effect was found for the difference in stimulation setup. Although there was a significant interaction of setup with NoP, both setups showed an increase in reported intensity with increasing NoP (see Supplementary materials). The quality scores are presented in Fig. 2b. There is an overall trend of increasing quality score with increasing NoP, this increase is significant. A total of 45 electrodes scored a quality score higher than 5, which is more toward that sharp end of the scale than toward the dull end. As was the case for the intensity scores, there is no significant main effect for the difference in setup, but there was an interaction of *Setup* with *NoP*, which for both setups is caused by an increase in quality score with increasing NoP (see Supplementary materials).

As a final test for the quality scores, we checked whether the surface electrodes received a significantly lower (more dull) quality score than the needle electrodes, which was the case [$F(1,322) = 232$, $p < 0.001$], with a mean quality score of 8.3 for the needle electrodes and 3.8 for the surface electrodes.

The reported qualities and intensities differed between the participants equipped with the two different electrode layouts. However, both methods influenced stimulus intensity and quality in the same manner, albeit to a slightly different degree. Therefore, the two setups do not differ in a relevant way and all localization data were subsequently pooled for analysis.

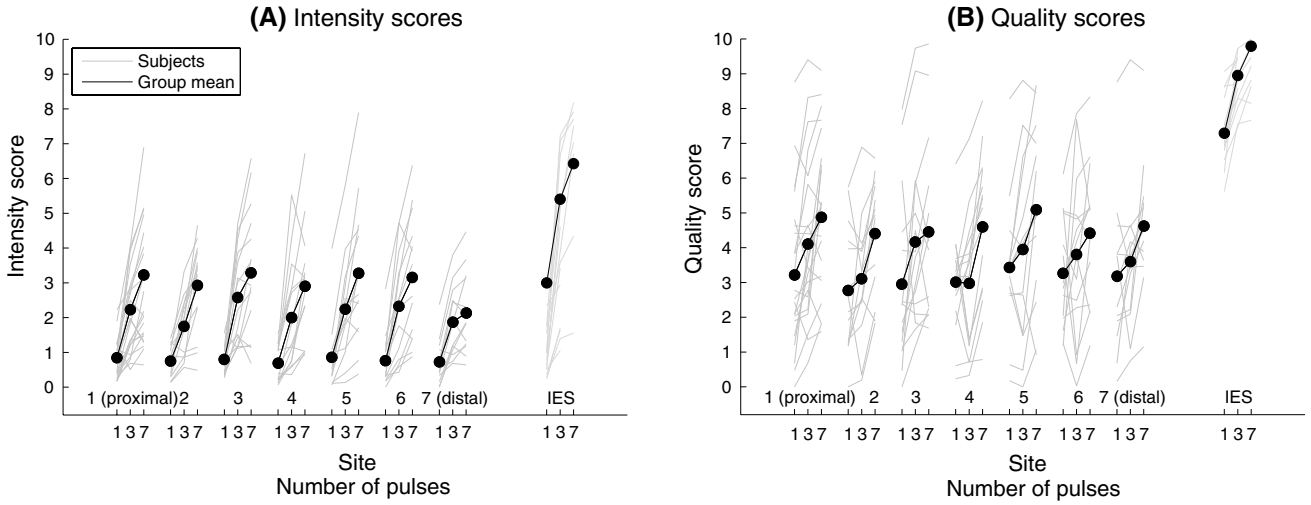



**Fig. 2** Group average and participant averages of the intensity and quality scores for each site and number of pulses. The scores are presented in ascending NoP and grouped per stimulus site. IES (intra-epidermal stimulation) refers to the needle electrodes, which were used for the nociceptive reference stimulus

**Table 1** Linear mixed model repeated measures analysis of intensity (log transformed) and quality scores

| Factor | Log intensity | | | Quality | | |
|---|---|---|---|---|---|---|
| | *df*[a] | *F* | *p* | *df*[a] | *F* | *P* |
| Stimulus site[b] | 6/41 | 1.84 | .114 | 6/52 | 1.49 | .202 |
| NoP[c] | 2/153 | 106 | <.001 | 2/137 | 14.9 | <.001 |
| Setup[d] | 1/13 | .021 | .887 | 1/13 | .258 | .620 |
| Stimulus site[b] × NoP[c] | 12/37 | .464 | .923 | 12/41 | .358 | .971 |
| NoP[c]*setup[d] | 2/160 | 4.90 | 0.009 | 2/116 | 3.40 | 0.037 |

[a] *df* approximate numerator/denominator degrees of freedom, [b] stimulus site is modeled as factor, [c] *NoP* number of pulses, [d] setup is a between-subjects factor

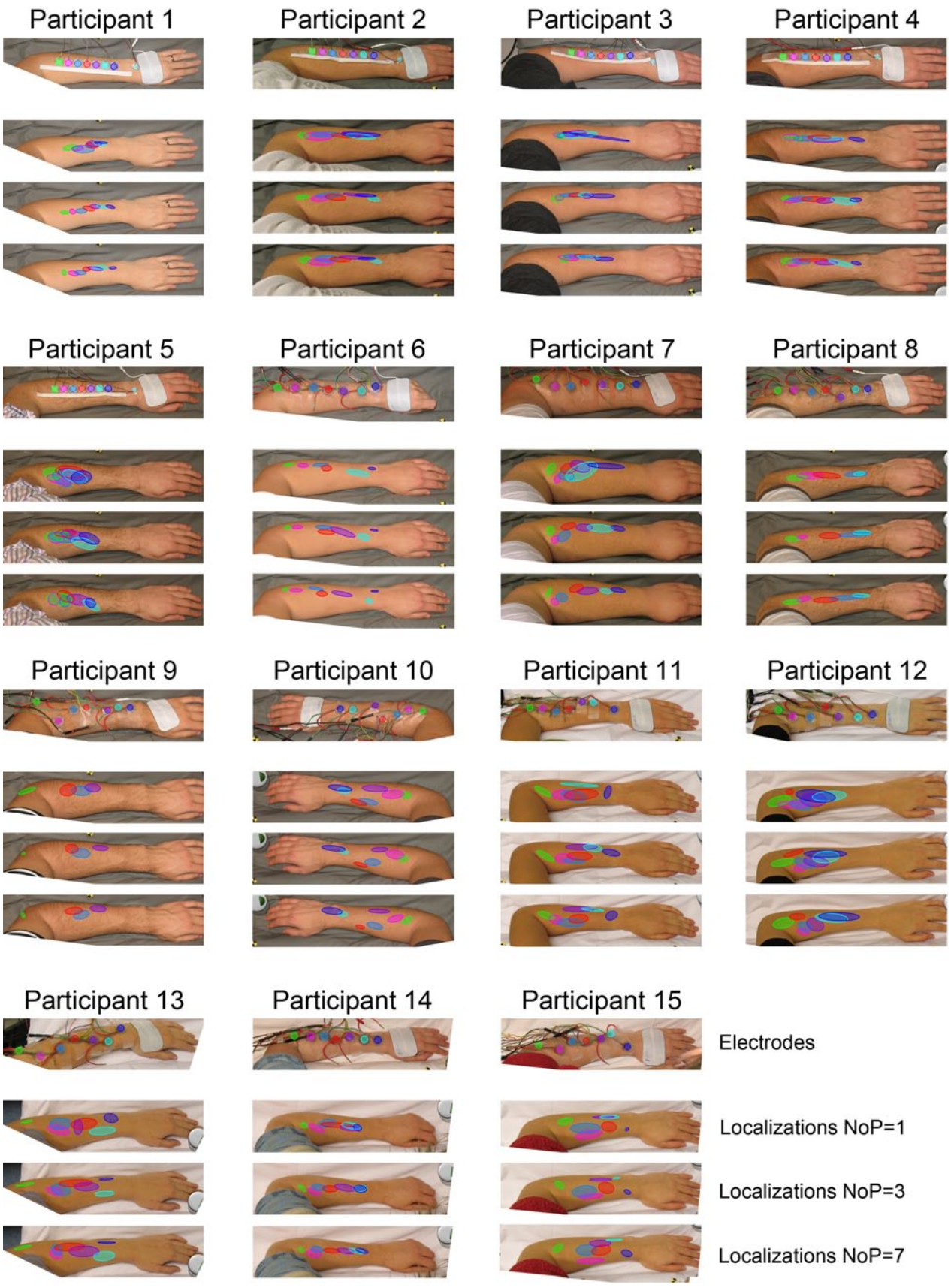
## Localizations

The localization data projected on the participants' arms along with the electrode placements are presented in Fig. 3. The localization patterns vary considerably between subjects, both with regard to the means and to the SDs. Linear regression fits of each separate participant are provided in the Supplementary materials.

### *Perceptual maps*

The results of the LMM analysis on the localization trials are presented in Table 2. The analysis revealed a significant effect of NoP, *Stimulus site,* and the interaction between these, which means that the slope of the regression model of localization as function stimulated site differs between intensity levels. No significant effects for *Repetition* and its interaction with *Stimulus site* were found, indicating that localizations did not drift in the course of the experiment. The LMM as function of the significant predictors can be interpreted as a linear regression model of the group-level perceptual map and is presented in Fig. 4. The figure shows the model fit as three linear regression fits, one for each intensity level. The regression model at the group level moves toward veridical (an intercept 0 and slope of 1) with increasing NoP.

**Fig. 3** Perceptual maps of all participants for each experiment▶ condition. The figure shows for each participant from top to bottom: *1* the electrode placement, *2* the means and standard deviations of the NoP = 1 stimuli, *3* for the NoP = 3 stimuli and *4* for the NoP = 7 stimuli. The localizations are plotted as means with standard deviations in two directions. The orientation of the standard deviation ellipses was determined by applying a principal component analysis on the localization data of the separate electrodes. The electrodes and localizations have been color coded (electronic version only)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Participant 14
Participant 15
Electrodes
Localizations NoP=1
Localizations NoP=3
Localizations NoP=7

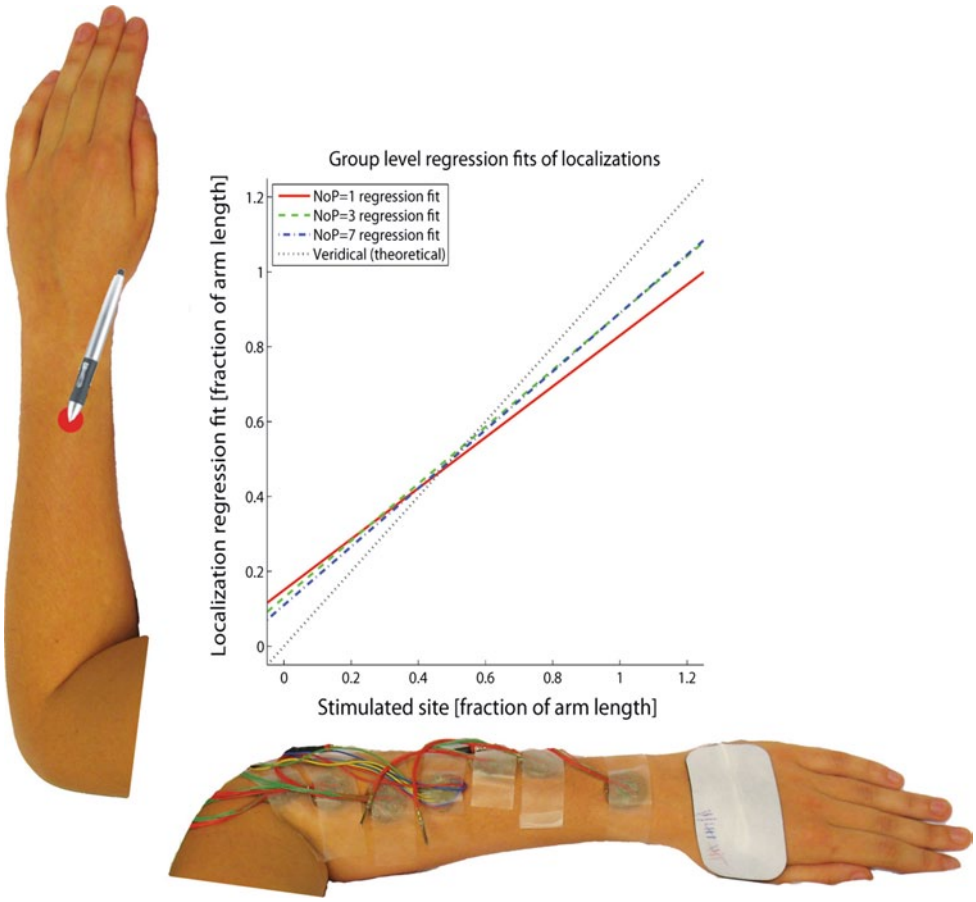


**Fig. 4** Regression fits of the group-level perceptual maps. The figure shows the model fits of the linear mixed model (LMM) on the data of all participants for the three levels of stimulus intensity. Example arms (participant 11) with and without electrodes are shown as reference

**Table 2** Linear mixed model significance tests of localization data

| Factor | *df*[a] | *F* | *p* |
|---|---|---|---|
| NoP[b] | 2/5,207 | 5.76 | .003 |
| Stimulus site[c] | 1/15 | 264 | <.001 |
| Repetition | 1/23 | 1.70 | .205 |
| NoP[b] × stimulus site[c] | 2/5,207 | 28.9 | <.001 |
| NoP[b] × repetition | 2/5,206 | 1.34 | .250 |
| Repetition × stimulus site[c] | 1/5,222 | .311 | .577 |

[a] *df* approximate numerator/denominator degrees of freedom, [b] *NoP* number of pulses, [c] stimulus site is modeled as covariate

### *Trial-to-trial variance*

The standard deviations of the localizations of each participant, site, and NoP are shown in Fig. 5a. The repeated measures analysis (see Table 3) revealed a significant main effect of *Site*, which Fig. 5a shows to reflect a decrease in SD in the distal to proximal direction. Although the effect of NoP differs between participants and sites, on average, there is a significant downward trend in the SD with increasing NoP. No significant main effect of *High-/low-quality score* or interaction with NoP was found.

### *Systematic localization error*

The regression fit obtained through the LMM as well as most of the participant-level regression fits moves toward a slope of 1 and intercept of 0 for increasing NoP. This could mean that the perceptual maps move toward veridical for increasing NoP. To find out whether participants make smaller systematic errors for higher NoP, we tested whether the localizations of the separate electrode sites also move toward veridical with increasing NoP. Figure 5b presents the relative systematic errors for participants and experiment conditions; in many of the cases, the error decreases for an increasing NoP, but not for all. This reduction in the systematic error was significant (Friedmans' ANOVA: $\chi^2(2) = 27.2, p < 0.001$).

None of the three tests for significant differences between sites with high- and low-quality score for each of the stimulus levels was significant (see Supplementary materials for details).

## Discussion

We performed a series of experiments to study the effect of stimulus intensity on localization of cutaneous stimuli.

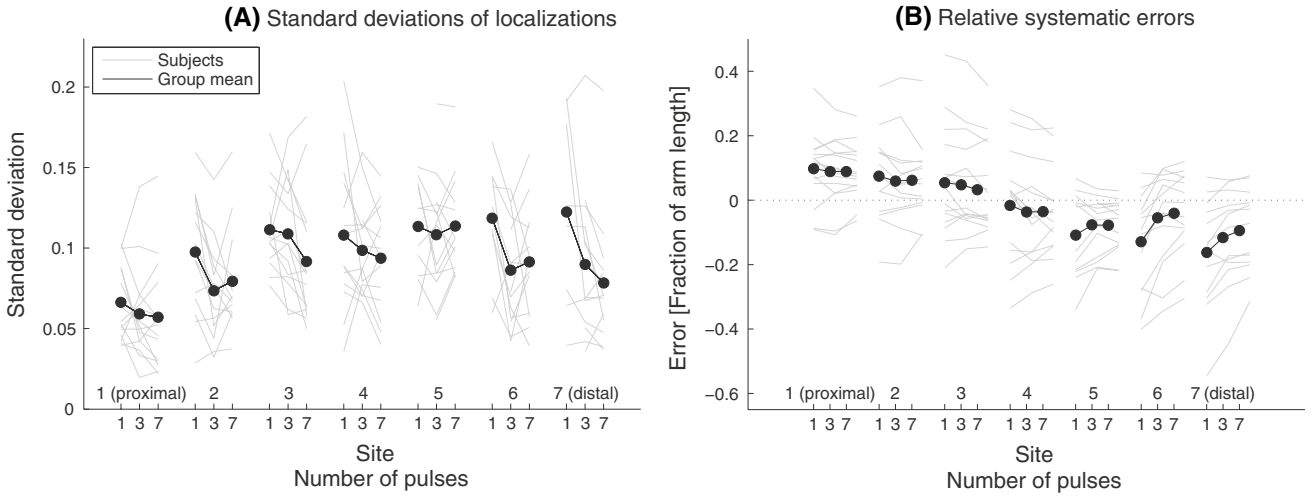


**Fig. 5** **a** Standard deviations (SD) of all sites and participants for each NoP along with the group average. Note than an averaged SD is not the SD of all pooled data. **b** Relative systematic localization errors. The figure presents the mean difference between the localization of each electrode and the electrode position of all sites and participants (*gray*) and the group means

**Table 3** Repeated measures analysis on localization standard deviations

| Factor | *df*[a] | *F* | *p* |
|---|---|---|---|
| Stimulus site[b] | 6/40 | 28.1 | <.001 |
| NoP[c] | 2/78 | 7.35 | .001 |
| Stimulus site[b] × NoP[c] | 12/37 | .876 | .577 |
| High quality[d] | 1/199 | 2.27 | .134 |
| NoP[c] × High quality[d] | 2/124 | 1.38 | .256 |

[a] *df* numerator/denominator degrees of freedom, [b] *NoP* number of pulses, [c] stimulus site is modeled as factor, [d] between-subjects factor distinguishing the sites with high- and low-quality scores at NoP = 7

Non-painful electrocutaneous stimuli were applied at seven sites on the lower arm. Three levels of stimulus intensity were applied using a pulse train modulation paradigm. As hypothesized, increasing the physical stimulus intensity led to a decrease in standard deviations at the group level. This indicates that participants responded more consistently with increasing stimulus intensity. Furthermore, the mean localization errors decreased with increasing stimulus intensity, which can be interpreted as an increase in localization accuracy.

Participants reported over a contracted length, which increased toward veridical with increasing stimulus intensity. Not all stimulus sites contribute to this effect to same extent, since the most distal electrodes have a larger decrease in mean mislocalization with increasing intensity than the proximal ones. This expansion of the reported length may be the result of participants relying on a default position on the arm when localizing weak stimuli, but relying increasingly on the actual stimulus locations with increasing stimulus intensity.

Our intention was to apply non-nociceptive stimuli. However, the quality ratings that participants assigned to the stimuli were often in the sharp part of the quality scale. In previous work, we associated this with nociceptive activity (Steenbergen et al. 2012b). In the present study, quality and intensity scores were both affected by NoP. This suggests that the effects of intensity on localizations may be confounded by an effect of stimulus quality. In order to assess whether this was a major influence, we split the data into high-quality and low-quality halves and analyzed whether this distinction had a significant effect on localization SDs and absolute systematic errors. No significant effects of high/low quality were found. From this we conclude that, if there is an effect of increasing nociceptive content with increasing NoP, this effect was minor and that the effects of NoP on localization we found are due to an effect of stimulus intensity.

The effect of NoP on quality score was different than what we found in an earlier study (Steenbergen et al. 2012b). There, the quality score for surface electrode stimuli was only slightly affected by NoP. However, the quality scores in the present study cannot be directly compared to those previous results because of differences in experiment design. In the current study, the vast majority of the stimuli during the quality scoring procedure were the surface electrode stimuli, which we wanted to assess, together with a small number of nociceptive IES stimuli which were added as a reference. In our previous study, on the other hand, the number of *dull* surface electrode stimuli and *sharp* needle electrode stimuli were equal. Possibly, the unequal number of sharp and dull stimuli in the present study biased the quality scores. Furthermore, because of time constraints, we only included four

scoring trials for each stimulus, whereas in the previous study, this number was 30, the quality scores of which varied considerably between trials.

Increasing the perceived stimulus intensity by varying the number of pulses in a stimulus is just one way in which the reliability, and consequently the trial-to-trial variance, of information about a stimulus can be modified. Stimulus duration and area may also influence reliability of sensory information. Because of differences in central processing between various cutaneous modalities, the parameters that influence the reliability of sensory information may affect perception of these sensory modalities differently. We recently presented a paper in which we studied the difference in localization between electrically elicited tactile and nociceptive electrocutaneous stimuli. We found that in individual participants, tactile and nociceptive localizations differed. However, these differences were not consistent between participants. We suggested that a difference in stimulus intensity may have contributed to this and that the effects we found therefore may not have been caused by a difference in tactile and nociceptive spatial perception. On the basis of the current study, we cannot conclude whether this was indeed the case, but suggest that a study be set up in which localization of touch and nociception is compared and in which stimulus intensity is varied for both modalities. We expect to find the same effects for nociceptive stimuli as we found for tactile stimuli in the present study. Due to differences in central processing, the magnitude of these effects may differ between modalities. If there is indeed an effect of both stimulus intensity and modality on localization, the chaotic differences we found between tactile and nociceptive localizations in individual participants have to persist in addition to the effects of stimulus intensity.

Perceptual maps of somatosensory stimuli may provide a means of studying distortions in spatial perception in patients suffering from pathologies, which go hand in hand with anomalous body perception, such as eating disorders (Guardia et al. 2010; Nico et al. 2010; Urgesi et al. 2011), fixed dystonia (Edwards et al. 2011), phantom sensations, and complex regional pain syndrome (Reinersmann et al. 2012). If perceptual maps are to be used for studying abnormal perception, then full knowledge is required about the way in which perceptual maps can vary in healthy participants and about the influences that are responsible for these changes. This includes multimodal influences, like the effect of gaze direction (Harrar and Harris 2009), but also of various stimulus parameters such as stimulus modality (Mancini et al. 2011; Steenbergen et al. 2012a) and the effect stimulus intensity which we presented in the current paper. As discussed above, more parameters may be relevant in this respect.

We conclude that varying the intensity of a cutaneous stimulus affects both the consistency and accuracy of the responses in localization experiments. The trial-to-trial variance drops with higher stimulus intensity, while the perceptual maps move toward veridical, an effect that is connected to a reduction in the systematic error. For the intensities used in the current study, some distortions of perceptual maps remained for most participants.

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