Received: 20 November 2022 | Accepted: 18 June 2023

DOI: 10.1002/aur.2979

RESEARCH ARTICLE

No differences in implicit hand maps among different degrees of autistic traits

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Funding information

Japan Society for the Promotion of Science

Abstract

People with autism spectrum disorder (ASD) or higher levels of autistic traits have atypical characteristics in sensory processing. Atypicalities have been reported for proprioceptive judgments, which are tightly related to internal bodily representations underlying position sense. However, no research has directly investigated whether self-bodily representations are different in individuals with ASD. Implicit hand maps, estimated based on participants' proprioceptive sensations without sight of their hand, are known to be distorted such that the shape is stretched along the medio-lateral hand axis even for neurotypical participants. Here, with the view of ASD as falling on a continuous distribution among the general population, we explored differences in implicit body representations along with autistic traits by focusing on relationships between autistic traits and the magnitudes of the distortions in implicit hand maps ($N \sim 100$). We estimated the magnitudes of distortions in implicit hand maps both for fingers and hand surfaces on the dorsal and palmar sides of the hand. Autistic traits were measured by questionnaires (Autism Spectrum [AQ] and Empathy/Systemizing [EQ-SQ] Quotients). The distortions in implicit hand maps were replicated in our experimental situations. However, there were no significant relationships between autistic traits and the magnitudes of the distortions as well as within-individual variabilities in the maps and localization performances. Consistent results were observed from comparisons between IQ-matched samples of people with and without a diagnosis of ASD. Our findings suggest that there exist perceptual and neural processes for implicit body representations underlying position sense consistent across levels of autistic traits.

Lay Summary

Atypicalities related to autism spectrum disorder (ASD) have been reported for position sense, our ability to tell where our body parts are even when we cannot see them. People's internal hand images, estimated based on judgments of where different parts of the hands were located without seeing the hand, are shown to be distorted against the physical shapes, even in the general population. We investigated relationships between autistic traits and the distortions in internal hand images in the general population. We found no significant relationships between these measurements. Consistent results were observed from comparisons between people with and without ASD. These findings suggest that the perceptual and neural processes for internal body images are consistent across different levels of autistic traits.

KEYWORDS

autism spectrum disorder, autistic traits, body representations, hand, proprioception, psychometrics

INTRODUCTION

Autism spectrum disorder (ASD) is a neurodevelopmental disorder with typical features including difficulties in social communication and interactions, and irregularities in behavior, such as restricted and repetitive interests (American Psychiatric Association, 2013). Current understanding is that ASD-like characteristics are not unique to those with a formal diagnosis, but rather common properties falling on a continuous distribution among the general population (Baron-Cohen, 1995; Baron-Cohen et al., 2001; Frith, 1991; Wheelwright et al., 2010; Woodbury-Smith et al., 2005). Atypical sensory processing (e.g., hyper- and hypo-reactivity) was recently added as a diagnostic criterion of ASD (American Psychiatric Association, 2013), and has been reported in individuals with the diagnosis of ASD (Robertson & Baron-Cohen, 2017) and the general population along with measurements of autistic traits (e.g., Yaguchi & Hidaka, 2020).

Atypical sensory characteristics in ASD are related to difficulties in social communication and repetitive behavior or interests (Baum et al., 2015; Jeste & Nelson 3rd., 2009; Leekam et al., 2011). Specifically, touch is a fundamental sensory modality to establish abilities of social communications (Harlow & Zimmermann, 1959; McGlone et al., 2014). Notably, relationships between social abilities and tactile processing have been reported in ASD. For example, variability of sensitivities to touch in daily life situations is associated with difficulties in social communication in people with the diagnosis of ASD (Baranek et al., 1997; Hilton et al., 2010). A human brain imaging study also reported a positive correlation between brain activity in response to tactile stimuli and social communication difficulties in ASD (Cascio, Moana-Filho, et al., 2012). Studies on ASD have focused on basic processing such as detection and discrimination related to tactile sensation to external inputs so far (Blakemore et al., 2006; Cascio et al., 2008; Güçlü et al., 2007; Puts et al., 2014). Tactile judgments involving internal proprioceptive sensations, which are tightly related to bodily representations underlying position sense (Longo et al., 2010; Tamè et al., 2019), have also been a focus of research. For example, an observational study reported that children diagnosed with ASD had difficulties with proprioceptive processing such as planning and executing body movements (Blanche et al., 2012). The rubber-hand illusion, in which the simultaneous stimulation of a participant's hidden hand and a visible rubber hand creates the illusory ownership of the rubber hand (Botvinick & Cohen, 1998), occurred less persistently in children diagnosed with ASD than in children without the diagnosis (Cascio, Foss-Feig, et al., 2012). Similarly, people diagnosed with ASD (Greenfield et al., 2015; Paton et al., 2012) and those with higher autistic traits (Ide & Wada, 2017) showed atypical behavioral responses indicating weaker magnitudes of the rubber-hand illusion. The smaller magnitudes of the rubber-hand illusion indicate that the proprioceptive sensation for the participant's own hand is more reliable for people diagnosed with ASD against the presentation of a visible rubber that affects the proprioceptive sensation of the invisible participant's hand. Taken together with the finding that people diagnosed with ASD rather have difficulty suppressing visual distractors in simple visuo-tactile attention tasks (Poole et al., 2018), these experimental findings suggest that individuals with ASD and those with higher autistic traits have a stronger dependency on their proprioceptive sensations (Haswell et al., 2009; Wada et al., 2014).

It has been argued that people with ASD and higher autistic traits have atypical proprioceptive sensations and self-bodily image such as estimations of body size (shoulder width) (Asada et al., 2018) and self-other boundaries (Noel et al., 2017). To the best of our knowledge, however, no research has directly investigated whether self-bodily representations are different with ASD. Here, we focused on implicit hand maps estimated based on proprioceptive localization judgments (see reviews for Longo, 2015, 2022). Longo and Haggard (2010) asked participants to judge the location of the knuckles and tips of their fingers by placing the tip of a long baton on a board on top of the occluded hand. Judged locations were cued verbally so that the participants made responses purely based on their proprioceptive sensations. An implicit geometric map of the hand was estimated based on the relative relationships among the judged locations (Figure 1c). The authors demonstrated that the shape of the implicit hand map was distorted such that it was stretched along the medio-lateral hand axis and shrunk along the proximo-distal axis. Similar distortions have been shown on landmarks of an equidistant 3×3 grid (marker) on a hand surface with localization cues such as visual landmarks on a hand silhouette (Hidaka et al., 2020; Longo, Mancini, & Haggard, 2015) (Figure 1a,d). The distortions have been reported with tactile stimulations having both tactile and proprioceptive information (Hidaka et al., 2020; Longo, Mancini, & Haggard, 2015) and for body parts other than the hand such as the forearm (Longo, 2017), leg (Stone et al., 2018), and face (Longo & Holmes, 2020; Mora et al., 2018). Whereas the origins of the distortions of implicit hand maps remain under discussion, one of the possible causes could be low-level perceptual and neural processes involving proprioceptive sensation (Longo, 2022).

The aim of this study was to explore relationships between ASD and these implicit hand representations. With the view of ASD as falling on a continuous distribution among the general population (Baron-Cohen, 1995; Frith, 1991), we mainly focused on relationships between autistic traits and the magnitudes of the distortions in implicit hand maps underlying position sense in the general population.

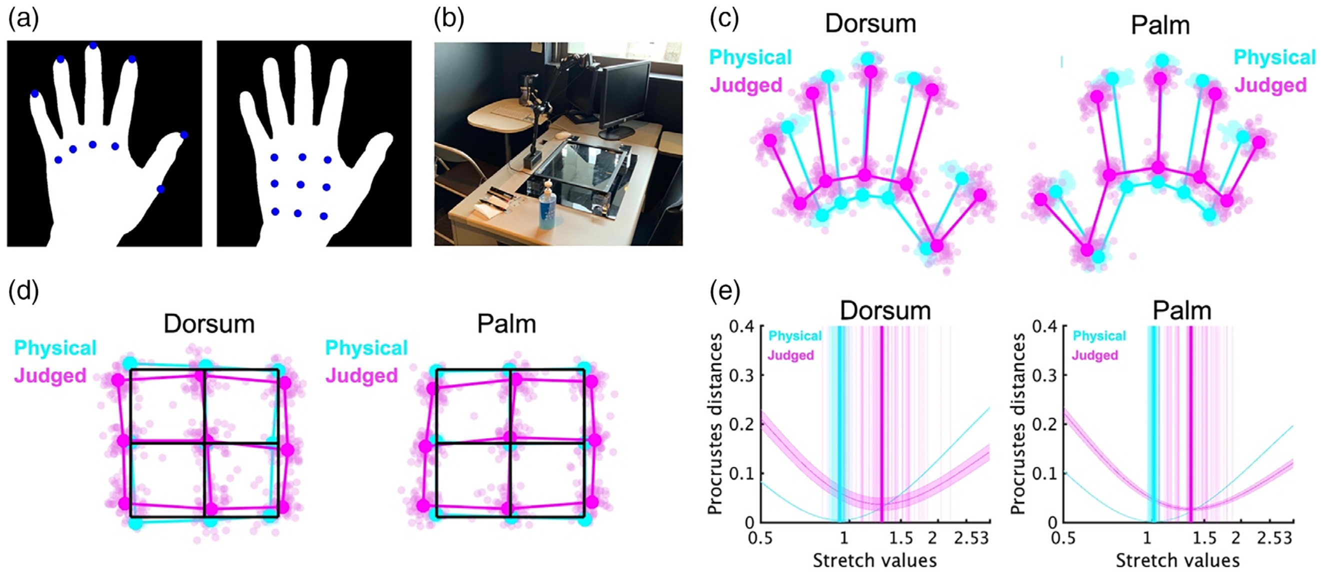

FIGURE 1 (a) Silhouette hand images for a dorsal hand surface. Each localized position on participant's left hand was cued by visual cues (blue dot). (b) Photo image of experimental setups. (c, d) Results of the proprioceptive localization for the finger (c) and marker (d) tasks on each hand surface. Each panel shows the whole map representing the judged locations. In (d), the whole maps are depicted against an idealized square grid (black line). (e) The estimated minimum Procrustes distances for the marker tasks. The horizontal axis denotes the stretch values. The vertical axis denotes Procrustes distances. The larger values indicate the stretch toward the medio-lateral axis and shrunk with along the proximo-distal axis. In (c), (d), and (e), the cyan and magenta plots indicate the physical and judged data, respectively. Plots with light colors show the individual data. The darker plots show the means.

As measurements of autistic traits, we used the Autism Spectrum Quotient (AQ) (Baron-Cohen et al., 2001) and Empathy and Systemizing Quotients (EQ and SQ) (Wheelwright et al., 2006) questionnaires. The AQ is a self-reported questionnaire developed to assess general tendencies of ASD. The scores have been shown to be distributed among individuals with higher scores indicating a greater magnitude of autistic traits, as people with the diagnosis of ASD showed larger AQ values (Baron-Cohen et al., 2001; Woodbury-Smith et al., 2005). The EQ and SQ have been developed to measure empathizing (i.e., sensitivity to social cues and the tendency to have concomitant emotional reactions with others) and systemizing (i.e., a focus on detecting the abstract rules that govern systems, as in specific classification characteristics or understanding number patterns) aspects related to ASD (Baron-Cohen et al., 2003; Baron-Cohen & Wheelwright, 2004; Wheelwright et al., 2006). The scores of EQ and SQ have also been shown to be distributed among individuals, and smaller and larger scores of EQ and SQ, respectively, have been observed for people both with and without the diagnosis of ASD (Wheelwright et al., 2006). Moreover, it has been demonstrated that AQ scores are negatively and positively related to EQ and SQ scores, respectively (Wheelwright et al., 2006). Consistent with the fact that males showed a higher rate of the diagnosis of ASD (Loomes et al., 2017), previous studies reported higher AQ and SQ scores and lower EQ scores for males compared to females (Baron-Cohen et al., 2001; Wheelwright et al., 2006). This evidence regarding AQ, EQ, and SQ has been confirmed to apply cross-culturally; for example, findings obtained in the United Kingdom have been replicated in the Japanese population (Wakabayashi et al., 2004; Wakabayashi et al., 2006; Wakabayashi et al., 2007).

Implicit hand maps were estimated by a localization task with visual landmarks on a hand silhouette (Hidaka et al., 2020; Longo, Mancini, & Haggard, 2015) both for fingers and markers on the dorsum side of the hand surface (Hidaka et al., 2020; Longo & Haggard, 2010; Longo, Mancini, & Haggard, 2015). Based on the idea that people with the diagnosis of ASD and those with higher autistic traits have a stronger dependency on proprioceptive sensation (Haswell et al., 2009; Wada et al., 2014) and that low-level perceptual and neural processes of proprioceptive sensation could be the origin of the distortions in implicit hand maps (Longo, 2022), we predicted that the distortions of implicit hand maps would be different with different degrees of autistic traits. Since there was no evidence to support any direction of differences, we could not make any predictions about the direction of differences. The distortions of implicit hand maps on the palm were also measured because very similar but weaker magnitudes of the distortions have been reported on the palmer side, presumably due to differences in neural mechanisms such as peripheral nerve density, cortical magnification, and receptive field geometry (Longo & Haggard, 2012). Generally, people with the diagnosis of ASD are reported to have less variance in response (Rodriguez & Thompson, 2015). On the other hand, people with the diagnosis of ASD also show greater irregulates and variabilities in their motor performances (Cook, 2016). We thus investigated the relations between autistic traits and within-individual fluctuations in localization responses and the magnitudes of the distortions in implicit hand maps during the experiment. We also performed a traditional comparison between the people with and without the diagnosis in IQ-matched samples.

METHODS

Participants

Data collection was performed in two institutes in Japan (Rikkyo University and Research Institute of National Rehabilitation Center for Persons with Disabilities). One hundred fifteen people, including 20 individuals with a diagnosis of ASD, participated in this study. Two participants' data were excluded due to an experimental error (i.e., missing data). Data from two participants were also excluded from the marker task because a web camera or touch screen was displaced accidentally during the experiment (>0.44 cm). Furthermore, five and six participants' data were excluded from the finger and marker task data, respectively, because their hands were regarded as having moved during an experimental block (over 15% of their hand width). The remaining samples were 106 (mean [SD] = 22.23 [4.16] y; 65 females) and 105 (mean [SD] = 22.37 [4.25] y; 63 females) participants for the finger and marker task data, respectively (Table S1). These samples included IQ-matched samples of individuals with and without a diagnosis of ASD for the finger ($N = 36$, 18 each, 4 and 9 females, respectively) and marker ($N = 38$, 19 each [two additional participants compared to the finger task], 4 and 9 females, respectively) tasks (Table S2). Eleven participants were regarded as left-handed and one participant as ambidextrous, as assessed by a Japanese version of the FLANDERS handedness questionnaire (Nicholls et al., 2013; Okubo et al., 2014) (mean [SD] = 7.54 [5.79], the scores ranged from −10 to +10 with positive scores indicating more right-handedness). Further data exclusions were performed for each analysis based on a criterion of ±2 SD and visual inspections of Q–Q plots. We performed analyses using all participant data except for those comparing the IQ-matched samples with and without a diagnosis of ASD. The sample sizes for each analysis were described in the result section.

Before data collection, we performed a power analysis for a multiple linear regression using G*Power 3.1 software (Faul et al., 2009) with an medium effect size of $f^2 = 0.15$ (Cohen, 1988), alpha of 0.05, power of 0.8, and three predictors. This indicated that 77 participants were required. Our sample size was therefore appropriately powered to detect comparably sized effects. All participants reported no abnormalities in tactile or visual perception and were naïve to the purpose of the experiments. They were paid or given course credits for their participation and gave written informed consent before initiating the experiments. Written informed consent was also collected from parents if participants were less than 18 years old (three participants were 16 years old and two were 17). The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the local ethics committees at Rikkyo University (Reference number: 19-44) and National Rehabilitation Center for Persons with Disabilities (Reference numbers: 31-8, 2020-011). This study was not preregistered.

Stimuli and procedure

We implemented identical experimental setups, and procedures were kept very similar for both institutes. The experimental procedures were consistent with those in previous studies (Hidaka et al., 2020; Longo, Mancini, & Haggard, 2015). The study consisted of two parts: experimental and questionnaire sessions.

Experimental session

In the experimental session, we prepared each participant's silhouette hand image as a visual cue, and then asked to complete the finger and marker localization tasks.

In the finger task, the experimenter made marks on the dorsal and palmar surfaces of the participant's left hand with a cosmetic pen. The metacarpophalangeal joint of each finger was marked in red. Then, we took a photo image of each surface of the participant's hand with a web camera (1920 × 1080 pixels; Logicool HD Pro C920r, Logitech International S.A., Lausanne, Switzerland) suspended on a ball head tripod (Velbon QHD-63, Hakuba Photo Industry Co., Ltd., Tokyo, Japan) with a monopod and a magnetic foundation at 53 cm above a desk. The photo image was trimmed and converted to a silhouette hand image, and the positions of the landmark locations, metacarpophalangeal joint and tip of each finger for the finger task and 3 × 3 grid for the marker task, were marked as a blue dot (8 pixels) on silhouette hand images by a custom MATLAB (MathWorks, Natick, MA, USA) script (Figure 1a).

After these preparations, participants were asked to place their hands with palms up or down under a transparent touch panel (19 in., 1280 × 1024 pixels;

PPMT-IR-019GR, KEYTEC, Inc., TX, USA) fixed on four resting silicon pillars (6 cm high) with Velcro tape (Figure 1b). To prevent the hand from moving, Velcro tape was used to attach the middle of the index and ring fingers to a black plastic sheet placed on a table. A silhouette hand image was presented on a PC display (38 × 34 cm, 1280 × 1024 pixels) placed in front of the participants. The participant's hand was occluded by a black-colored cardboard box under the touch panel to prevent them from seeing their hand and markers. On each trial, the judged location was cued individually (Figure 1a) by a blue dot appearing on a silhouette hand image. The participant's task was to place the tip of a stylus pen (14 cm length, 5 mm diameter) on the touch screen directly above the location where they felt the judged location was on their hand. The experimenter pressed a space key on a keyboard to record *x–y* coordinates of localization. Participants were instructed to be precise in their judgments and avoid ballistic pointing or strategies such as referring to the outline of the hand. To ensure that they judged each landmark individually, the experimenter asked the participant to move the stylus pen to the right-side edge of the touch panel before the start of each trial. At the beginning and end of each session, a photograph of the participant's hand was taken to check that the hand had not moved during the task.

For the marker task, the procedures were identical to those with the finger task except for the judged locations (Figure 1a). The landmarks were distributed equally on a 3 × 3 grid in the middle of the hand and marked in black with a plastic template (5 cm on a side, an equidistant separation of 2.5 cm between each location). The three rows ran along the medio-lateral hand axis, while the three columns ran along the proximo-distal axis. The position of the matrix was set such that the middle column was along with the straight line between the metacarpophalangeal joint of the middle finger and the center of the wrist as in the previous study (Hidaka et al., 2020).

The experiment consisted of 120 trials (10 locations × 2 hand surfaces [dorsum/palm] × 6 repetitions) for the finger task and 108 trials (9 locations × 2 hand surfaces [dorsum/palm] × 6 repetitions) for the marker task (228 trials in total). The order of the hand surfaces tested was counterbalanced across participants. The order of the finger/marker tasks was introduced as ABBA design and counterbalanced across participants. Thus, each participant completed 4 blocks (e.g., finger–dorsum, finger–palm, marker–palm, and marker–dorsum). In each block, the presentation of the judged locations was pseudorandomized such that the order of the locations was randomized in each repetition. The experiment was controlled by Psychtoolbox-3 (Brainard, 1997; Pelli, 1997) and a custom MATLAB script with a computer (Mac Pro or Mac mini; Apple, Inc., CA, USA). We also used an eye mask, a black cloth, and a partition to prevent participants from seeing their hands and arms during the experiment.

Questionnaire session

After completing the experimental session, participants were asked to fill in questionnaires. For the measurements of autistic traits, we used the Japanese version of the AQ (50 items) (Wakabayashi et al., 2004) and the Japanese version of the short form of EQ-SQ (47 items) (Wakabayashi et al., 2006). For some participants in the Research Institute of National Rehabilitation Center for Persons with Disabilities, we used the scores collected in another experimental situation performed within a few weeks. We also introduced another questionnaire but analyses for these were out of the scope of this study.

For comparisons between IQ-matched samples of people with- and without-diagnosis of ASD, 40 participants including those with the diagnosis of ASD ($N = 20$) received a Japanese version (Fujita et al., 2006) of the Wechsler Adult Intelligence Scale-III (Wechsler, 1997). The participants with ASD also received the Japanese version (Kuroda & Inada, 2015) of the Autism Diagnostic Observation Schedule Component, Second Edition (ADOS-2; Lord et al., 2012).

Data analysis

We analyzed the coordinate data obtained from participants' localization judgments and physical hand as the whole map for the finger and marker tasks as in previous studies (Hidaka et al., 2020; Longo, Mancini, & Haggard, 2015). As for the finger task, we also performed analyses for the length and width of the fingers separately (Longo & Haggard, 2010; Longo, Mattioni, & Ganea, 2015) because independencies of these data have been reported (Coelho & Gonzalez, 2019; Longo, 2019; Longo, Mattioni, & Ganea, 2015).

The x-y pixel coordinates recorded on the touch panel during the experiment were analyzed for participants' localization judgments. We also performed offline coding for the photo images of participants' hands as physical hand data. Each photo image was displayed on a computer display (1600 × 1200 pixels) and the *x–y* pixel coordinates of each landmark were recorded by a mouse click as in previous studies (Hidaka et al., 2020; Longo, Mancini, & Haggard, 2015). The *x–y* pixel coordinates of the top-left and the top-right edge of the touch panel (frame coordinate) were also recorded. The distance between the coordinates was calculated as Euclidean distance in our analyses.

In pre-processing, we first checked whether the camera or the touch panel was moved or not during the experiment by comparing the frame coordinates at the beginning and end of each session. Based on the results of offline data coding, we regarded the displacement of the frame coordinates over 11 pixels (approximately 0.22 cm: 38 cm of the frame distance/1920 pixel) as a threshold. Two data showing the displacements of the frame coordinates over 22 pixels (0.44 cm) were excluded for each dorsum and palm session of the marker task. Then, we checked whether the participant's hand had moved or not. We calculated the mean for the displacements of the x–y pixel coordinates among each landmark for each participant. Then, the means of the displacements were divided by the distance of each participant's hand width (Hidaka et al., 2020). We checked the distribution of log-converted values of this hand movement index (i.e., hand displacement against hand width for each participant), and regarded the displacement over 15% as a threshold (2 SD of the distribution was 16.05%). Six (one for dorsum, five for palm) and five (all for palm) participants' data were excluded from the finger and marker tasks, respectively. We excluded the participants' data over ±2 SD in each dependent variable.

We estimated four dependent variables (aspect ratio, distortion index, variability index, and overestimation index) for each task and hand surface in analyses for the whole map. First, we calculated the aspect ratios of vertical and horizontal distances in physical and implicit hand maps. As for the finger task, we calculated a ratio of width to length of the hand (Longo & Haggard, 2010). The distance between the metacarpophalangeal joints of the index and little fingers was calculated as width and that between the tip and bottom of the middle finger as length for each participant. The ratio was log transformed.

As for the marker task, we used a method called Procrustes alignment (Bookstein, 2009; Rohlf & Slice, 1990). This allowed us to compare and estimate co nfigurations of homologous landmarks by translating, rotating, and scaling them so as to minimize the distance between homologous pairs of landmarks. We used generalized Procrustes analysis (Surhone et al., 2010), implemented in the shape analysis MATLAB toolbox developed by Simon Preston (University of Nottingham, https://www.maths.nottingham.ac.uk/plp/pmzspp/shape.php), to superimpose a whole map obtained from each participant on an idealized square grid reflecting the location of the 9 equidistant points. We then estimated grand-average maps by averaging all participants' superimposed data. This visualization technique was also used for the finger task data (Figure 1c,d).

In addition to its use for data visualization, we also used Procrustes alignment to quantify the overall level of the aspect ratio in implicit hand maps for the marker task, as in previous studies (Hidaka et al., 2020; Longo & Golubova, 2017; Longo & Morcom, 2016). We used the Procrustes distance, the square root of the sum-of-squares of the residual distances between pairs of homologous landmarks, as a measure of the overall dissimilarity in shape between two maps. To determine the aspect ratio in physical and implicit hand maps, we stretched a perfect square grid reflecting the location of the 9 points by different amounts to find the stretch that maximized the similarity with each participant's hand map. Stretches were defined by the multiplication of the x-coordinate (reflecting location in the medio-lateral hand axis) by a stretch parameter. Stretch parameter values between 0.33 and 3 were tested by exhaustive search with a resolution of 0.0005 units in natural logarithm space (i.e., 4415 steps). For each participant, we determined the value of the stretch parameter that minimized the dissimilarity in shape (i.e., that minimized the Procrustes distance) between the stretched grid and the participant's hand map. A stretch value of 1 therefore indicates a perfectly square grid, a stretch of less than 1 indicates a tall thin grid, and a stretch of more than 1 indicates a squat fat grid.

To investigate the relationships between autistic traits and the distortions of implicit hand maps, we calculated a distortion index for each participant by subtracting the physical data from judged data of the log-transformed aspect ratios. Larger values indicate stronger distortions in implicit hand maps compared to the actual, physical shape of the hand.

As an index of variability of localization performances, we calculated the standard deviation of judged coordinates for each landmark across six repetitions and averaged them for each participant. The standard deviation of the aspect ratios for the finger and marker tasks across six repetitions was also calculated as a variation in the implicit hand maps for each participant.

We also estimated the amount of overestimation separately for the length and width of the fingers in the data of the finger task as in previous studies (Longo & Haggard, 2010; Longo, Mattioni, & Ganea, 2015). The distance between the tip and bottom of each finger and that between the metacarpophalangeal joints of the index and little fingers were calculated as the length and width, respectively, for the physical and judged data for each participant. The pixel distances were converted to cm with the frame coordinates data. We then calculated the amount of overestimation as the log-transformed ratios of the judged data divided by the physical data. The estimated overestimations for the finger length were also collapsed across fingers. The standard deviation of the lengths and widths of the fingers across six repetitions was also calculated.

We calculated AQ, EQ, and SQ scores based on the calculation method defined in previous studies (Baron-Cohen et al., 2001; Wakabayashi et al., 2004; Wakabayashi et al., 2006; Wheelwright et al., 2006). Higher AQ and SQ scores and lower EQ scores indicate stronger autistic traits. An occupational therapist, who had a research license for the ADOS-2, evaluated ADOS-2 score in each participant with ASD. Communication score (cutoff: 2 of 3), Social Interaction score (cutoff: 4 of 6), and Total score (Communication score + Social interaction score) (cutoff: 7 of 10) were calculated. The cutoffs mentioned in parentheses denote the minimum scores for evaluation for autism spectrum. In addition, Full IQ, Verbal IQ and Non-verbal IQ were calculated according to standard procedures for WAIS-III.

Before the main analyses, we checked whether the measurements were different between the institutions. Mann–Whitney *U* tests were performed for age, the distortion indices for dorsum and palm, AQ, EQ, and SQ scores for each finger and marker task ($\alpha = 0.05/6$ with Bonferroni correction). We found that age, SQ, and the distortion indices for dorsum (marker) and palm (finger and marker) were significantly different (Ws > 669.5, $ps < 0.008$; Table S3A). The chi-square test also found the number of males and females was also different between the institutions ($\chi^2 s > 15.66$, $ps < 0.001$). We also checked whether the measurements differed between the sexes because the differences in sex have been reported for autistic traits (Wheelwright et al., 2006) and implicit hand representations (Coelho & Gonzalez, 2019; Longo, 2019). The autistic traits differed between sex in our data ($\alpha = 0.05/5$) (Ws > 583.5, $ps < = 0.01$), while we did not find any differences in sex for the distortion indices (Ws < 1218.0, $ps > 0.10$ (Table S3B). We performed correlation analyses ($\alpha = 0.05/5$) regarding age because previous studies also reported age-related differences in AQ scores (Lodi-Smith et al., 2021). There were no significant correlations (Spearman's Rho) between age and autistic traits in our data ($\rho s < |0.13|$, $ps > 0.18$) (Table S3C). In contrast, we found significant negative correlations between age and the distortion indices for both hand surfaces in the finger data and for palmer surface in the maker data ($\rho s > -27$, $ps < 0.006$; Table S3C). We thus decided to include sex, age, and institution as covariates in the main analyses.

We performed an analysis of covariance (ANCOVA) for the aspect ratios in each task (finger or marker) with factors surface (2: Dorsum/Palm) and data (Judged/Physical) including participants, sex, age, and institutions as covariates. We also performed ANCOVAs for the distortion indices in each task (finger or marker) and the overestimations of length and width in the finger task with factors surface (2: Dorsum/Palm). An ANCOVA was also performed for the overestimations of the finger length with a factor finger (5: thumb, index, middle, ring, and little fingers).

We investigated the relationships between autistic traits and the distortion indices and judged length and width of fingers as well as variability in localization performance, implicit hand maps, and judged length and width of fingers by hierarchical multiple linear regression analyses using the forced entry method. First, we put sex, age, and institution as explanatory variables in a multiple linear regression model. Then, we entered the AQ, EQ, and SQ scores as explanatory variables into the model and tested whether the amount of regression significantly increased. This method enabled us to control possible effects of covariates and relationships between AQ, EQ, and SQ scores. We checked the normality of the residuals based on *Q–Q* plots (Figure S1) and excluded data by visual inspections of *Q–Q* plots if necessary.

We also performed Mann–Whitney *U* and chi-square tests to compare the IQ and demographic data between with- and without-diagnosis groups before the comparison of the IQ-matched samples. We compared the distortion indices and the overestimations of finger length and width as well as variabilities in localization performance, implicit hand maps, and judged length and width of fingers between the IQ-matched with- and without-diagnosis groups by Mann–Whitney *U* tests. The IQ-matched data were collected in one institute (Research Institute of National Rehabilitation Center for Persons with Disabilities) so no covariances were included in these analyses.

The data analyses were conducted using MATLAB, R software (version 4.0.3) with ggplot2 (Wickham, 2009), and JASP (JASP Team, 2022). The data have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/362ex/.

RESULTS

Distortions in implicit hand maps

We first checked whether our data showed the distortions of implicit hand maps described in previous research (i.e., the shape of the implicit hand map stretched toward the medio-lateral axis and shrunk along the proximo-distal axis). The ANCOVA for the aspect ratios in the whole map for both finger ($N = 89$) and marker ($N = 82$) tasks found significant main effects of data (Judged/Physical) for both tasks (Finger: $F(1{,}348) = 1714.24$, $p < 0.001$, $\eta^2_p = 0.83$; Marker: $F(1{,}320) = 490.56$, $p < 0.001$, $\eta^2_p = 0.61$), showing that the aspect ratio of the horizontal distance against the vertical was larger for the judged data (Figure 1c,d, Figure 2a). Consistent results were observed for the distortion indices (Figure 2b). The ANCOVA for both finger ($N = 97$) and marker ($N = 93$) tasks found that the means were significantly different from zero ($\alpha = 0.05/2$ with Bonferroni correction) in both surfaces (Dorsum/Palm; Finger: *ts* (188) > 30.28, $ps < 0.001$, $dzs > 4.42$; Marker: *ts* (180) > 15.47, $ps < 0.001$, $dzs > 2.31$) (Table S4A). The ANCOVA for the overestimation of the finger lengths in the implicit hand maps against the physical hand for the dorsum ($N = 85$) and palm ($N = 88$) (Figure 2c) found that the means were significantly smaller than zero (i.e., underestimation) in both surfaces for each finger ($\alpha = 0.05/5$; Dorsum: *ts* (416) < −11.32, $ps < 0.001$, $dzs < -1.11$; Palm: *ts* (431) < −7.80, $ps < 0.001$, $dzs < -0.75$) as well as significant main effects of finger (Dorsum: $F(4{,}416) = 28.87$, $p < 0.001$, $\eta^2_p = 0.22$; Palm: $F(4{,}431) = 14.46$, $p < 0.001$, $\eta^2_p = 0.12$; Table S4B). An ANCOVA with factor surface ($N = 96$) for the data collapsed across the fingers also showed that the means were

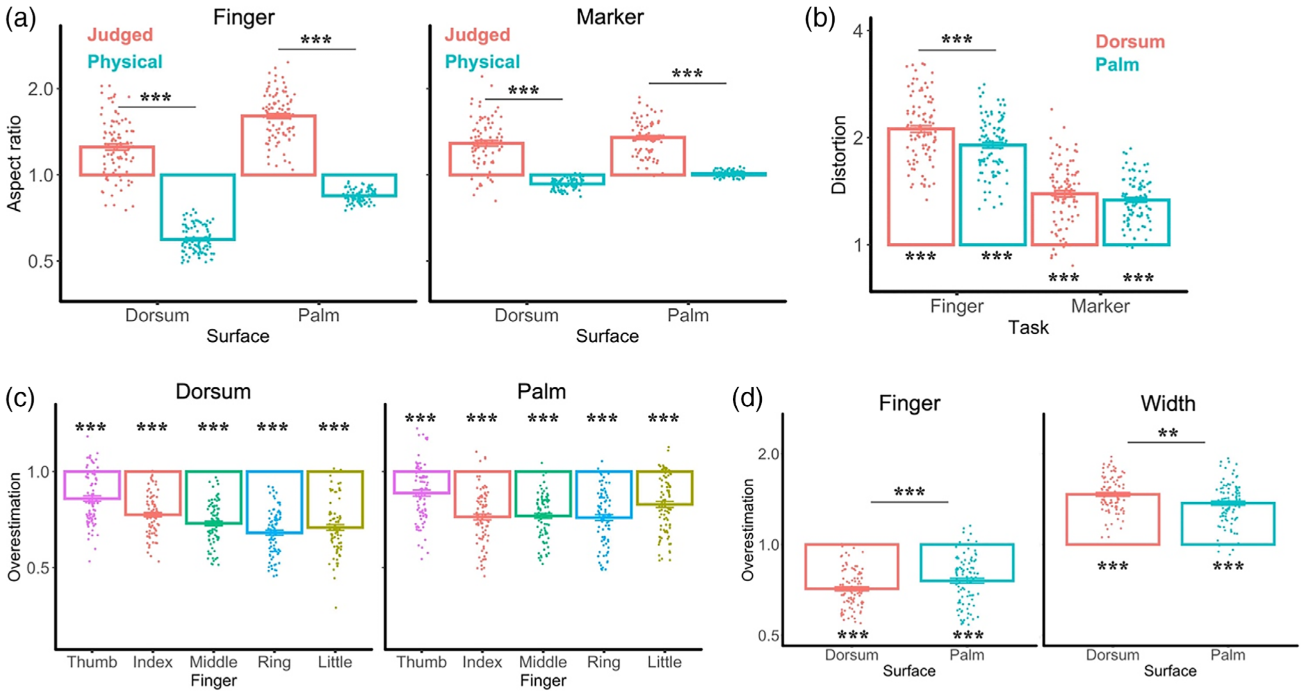

FIGURE 2 (a) Aspect ratios in the finger and marker tasks. The horizontal axis denotes the hand surface. The vertical axis denotes the aspect ratios of physical and implicit hand maps. Larger values indicate the stretch toward the medio-lateral axis and shrunk with along the proximo-distal axis. The cyan and magenta plots indicate the physical and judged data, respectively. (b) Distortion indices. The horizontal axis denotes the type of task. The vertical axis denotes an index of distortions in implicit hand maps against the physical hand maps. The cyan and magenta plots indicate the palm and dorsum data, respectively. (c) Overestimation indices for the finger length in the finger task. The horizontal axis denotes the fingers. In the vertical axis, the lower values compared to 1 indicate underestimations of the judged finger length against the physical data. (d) Overestimation indices for the finger length collapsed across fingers and the finger width in the finger task. The horizontal axis denotes the hand surface. The error bars denote the standard error of the mean. Each dot plots show the individual data. Asterisks denote statistical significances (** $p < 0.01$, *** $p < 0.001$).

significantly smaller than zero in both surfaces ($\alpha = 0.05/2$) ($ts(186) < -15.97$, $ps < 0.001$, $dzs < -2.34$; Figure 2d, Table S4C). As for the width ($N = 94$), the ANCOVA found that the means were significantly larger than zero (i.e., overestimation) in both surfaces ($\alpha = 0.05/2$) ($ts(182) > 18.36$, $ps < 0.001$, $dzs > 2.72$; Figure 2d, Table S4C). We also found larger distortions in implicit hand maps for the dorsal hand surface than the palmar surface in the finger task (Supplementary Texts).

These results clearly demonstrated the distortions of implicit hand maps both for the finger and marker tasks, replicating previous findings (Hidaka et al., 2020; Longo & Haggard, 2010; Longo, Mancini, & Haggard, 2015; Longo, Mattioni, & Ganea, 2015).

Relationships between autistic traits and distortions in implicit hand maps

To investigate the relationships between autistic traits and the distortions in implicit hand maps, we performed hierarchical multiple linear regression analyses for the distortion indices. In the first step, we did not find significant model-fit in the finger–dorsum and finger–palm data ($Ns = 97$, $Fs(3, 93) < 2.21$, $ps > 0.09$, adjusted R^2s < 0.04) and in the marker–dorsum data ($N = 93$, $F(3, 89) = 1.21$, $p = 0.31$, adjusted $R^2 = 0.01$). There was a significant model-fit for the marker–palm data ($N = 93$, $F(3, 89) = 4.36$, $p = 0.007$, adjusted $R^2 = 0.10$) with a significant effect of institutions ($t = 2.19$, $p = 0.03$; Table S5). In the second step, the inputs of AQ, EQ, and SQ scores did not induce any significant changes in the explanatory effect of the model both finger ($Fs(3, 90) < 0.06$, $ps > 0.14$, adjusted R^2s < 0.03, R^2 changes < 0.04) and marker ($Fs(3, 86) = 0.80$, $ps > 0.50$, adjusted R^2s < 0.08, R^2 changes < 0.03) tasks.

We also performed hierarchical multiple linear regression analyses for the overestimations of the length and width of the finger obtained in the finger task (Table S6). In the first step for the finger length ($Ns = 96$), we did find not a significant model-fit in the dorsum data ($F(3, 92) = 2.21$, $p = 0.09$, adjusted $R^2 = 0.04$) but a significant one for the palm data ($F(3, 92) = 2.78$, $p = 0.05$, adjusted $R^2 = 0.06$) with a significant effect of institutions ($t = -1.96$, $p = 0.05$). There were no significant changes in the explanatory effect of the model in the second step for both surface data ($Fs(3, 89) < 0.54$, $ps > 0.67$, adjusted R^2s < 0.04, R^2 changes < 0.02). Consistent results were obtained for both surfaces of the finger width

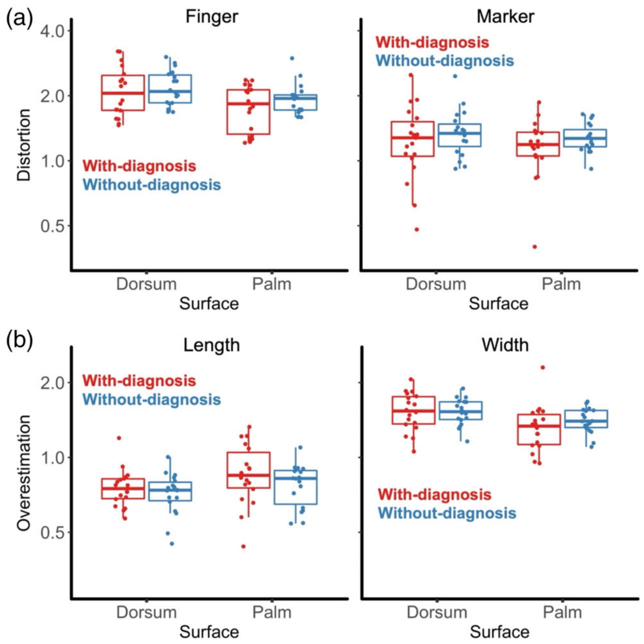

FIGURE 3 Distortions in the finger and marker tasks (a) and overestimations for the length and width in the finger task (b) for the IQ-matched samples. Each box plots show medians and the first and third quartiles. Error bars denote the maximum and minimum values within 1.5 times of interquartile range. The horizontal axis denotes the hand surface. The red and blue plots indicate the with- and without-diagnosis of ASD samples, respectively.

(Ns = 94) in the first (Dorsum: $F(3, 90) = 2.07$, $p = 0.11$, adjusted $R^2 = 0.07$; Palm: $F(3, 90) = 2.84$, $p = 0.05$, adjusted $R^2 = 0.09$) and second steps (Fs$(3, 87) < 1.35$, ps > 0.26, adjusted R^2s < 0.07, R^2 changes < 0.04).

These results showed no significant relationships between autistic traits and the distortions in implicit hand maps.

Relationships between autistic traits and variabilities in localization performances and implicit hand maps

We further investigated possible relationships between autistic traits and variability in localization performances and the implicit hand maps using hierarchical multiple linear regression analyses (Table S7). There were no significant changes in the explanatory effect of the model both for the finger and marker tasks and surfaces in the second step in the variabilities in localization performances (finger–dorsum ($N = 99$): $F(3, 92) = 1.26$, $p = 0.29$, adjusted $R^2 = 0.01$, R^2 changes $= 0.04$; finger–palm ($N = 94$): $F(3, 87) = 1.48$, $p = 0.23$, adjusted $R^2 = 0.08$, R^2 changes $= 0.04$; marker–dorsum ($N = 97$): $F(3, 90) = 0.72$, $p = 0.54$, adjusted $R^2 = 0.06$, R^2 changes $= 0.02$; finger–palm ($N = 97$): $F(3, 90) = 1.18$, $p = 0.32$, adjusted $R^2 = 0.09$, R^2 changes $= 0.03$).

The same tendencies were observed for variability of the aspect ratios in the whole map analyses (Table S8; finger–dorsum ($N = 98$): $F(3, 91) = 1.33$, $p = 0.27$, adjusted $R^2 = 0.03$, R^2 changes $= 0.04$; finger–palm ($N = 98$): $F(3, 91) = 0.93$, $p = 0.43$, adjusted $R^2 = 0.02$, R^2 changes $= 0.03$; marker–dorsum ($N = 97$): $F(3, 90) = 2.16$ $p = 0.10$, adjusted $R^2 = 0.18$, R^2 changes $= 0.06$; finger–palm ($N = 96$): $F(3, 89) = 0.89$, $p = 0.45$, adjusted $R^2 = 0.04$, R^2 changes $= 0.03$).

We also found no significant changes in the explanatory effect both for the length and width of fingers in the finger task (Table S9; length–dorsum ($N = 96$): $F(3, 89) = 0.45$, $p = 0.72$, adjusted $R^2 = 0.03$, R^2 changes $= 0.01$; length–palm ($N = 98$): $F(3, 91) = 0.51$, $p = 0.68$, adjusted $R^2 = -0.02$, R^2 changes $= 0.02$; width–dorsum ($N = 98$): $F(3, 91) = 2.06$, $p = 0.11$, adjusted $R^2 = 0.04$, R^2 changes $= 0.06$; width–palm ($N = 99$): $F(3, 92) = 1.27$, $p = 0.29$, adjusted $R^2 = 0.19$, R^2 changes $= 0.03$).

These results demonstrate no significant relationships between autistic traits and variabilities in responses and the shapes of implicit hand maps.

Comparisons of IQ-matched samples with and without the diagnosis of ASD

We also performed the standard comparison between people with- and without-diagnosis of ASD (Figure 3, Table S2). Mann–Whitney U tests ($\alpha = 0.05/7$ with Bonferroni correction) showed that IQ values as well as age were not significantly different between the samples both for finger and marker data (Ws < 224.0, $ps > 0.21$), whereas AQ scores for both tasks and EQ scores for the finger task differed significantly (Ws > 70.0, $ps < 0.004$) (Table S10). The chi-square tests confirmed that the number of males and females were not significantly different between the samples (X^2s < 3.01, $ps > 0.08$). Consistent with the findings reported in the previous sections, Mann–Whitney U tests ($\alpha = 0.05/6$) found that there were no significant differences in the distortion indices, variabilities in localization performances, and those in the implicit hand maps between the IQ matched samples (Ws < 141.0, $ps > 0.01$; Table 1). Consistent results were observed for the length and width of fingers in the finger task ($\alpha = 0.05/4$) (Ws < 179.0, $ps > 0.19$) (Table 2).

DISCUSSION

The current study investigated relationships between autistic traits and implicit hand representations underlying proprioceptive localization of the hand. Our data clearly replicated the distortions in implicit hand maps (i.e., the shape of the implicit hand map stretched toward the medio-lateral axis and shrunk along the proximo-distal axis) underlying position sense both for the finger

TABLE 1 Results of the comparison of the IQ-matched with- and without-diagnosis samples for the distortion indices and variabilities.

		Diagnosis					
		With		Without			
Surface	Label	Mean	SD	Mean	SD	W	p
Finger							
Dorsum	Distortion	0.73	0.26	0.77	0.19	141.00	0.52
	Localization variability	39.26	27.59	30.22	4.93	201.00	0.23
	Distortion variability	0.23	0.14	0.21	0.08	167.00	0.89
Palm	Distortion	0.56	0.25	0.65	0.16	148.00	0.67
	Localization variability	45.22	35.02	30.89	8.98	210.00	0.13
	Distortion variability	0.26	0.16	0.21	0.05	178.00	0.63
Marker							
Dorsum	Distortion	0.19	0.39	0.29	0.24	156.00	0.49
	Localization variability	−3.22	0.54	−3.66	0.50	265.00	0.01
	Distortion variability	8.02	0.28	7.89	0.23	230.00	0.15
Palm	Distortion	0.14	0.32	0.24	0.15	147.00	0.34
	Localization variability	−2.85	0.61	−2.99	0.66	200.00	0.58
	Distortion variability	8.10	0.29	7.98	0.23	225.00	0.20

TABLE 2 Results of the comparison of the IQ-matched with- and without-diagnosis samples for finger length and finger width.

		Diagnosis					
		With		Without			
Surface	Label	Mean	SD	Mean	SD	W	p
Finger length							
Dorsum	Overestimation	−0.28	0.17	−0.34	0.20	179.0	0.61
	Overestimation variability	0.70	0.65	0.51	0.15	194.0	0.32
Palm	Overestimation	−0.16	0.28	−0.26	0.20	196.0	0.29
	Overestimation variability	0.83	0.88	0.54	0.44	204.0	0.19
Finger width							
Dorsum	Overestimation	0.42	0.18	0.42	0.12	167.0	0.89
	Overestimation variability	1.16	1.23	0.98	0.39	142.0	0.54
Palm	Overestimation	0.27	0.21	0.34	0.12	117.0	0.16
	Overestimation variability	1.05	0.99	0.89	0.40	146.0	0.63

and marker tasks (Hidaka et al., 2020; Longo & Haggard, 2010; Longo, Mancini, & Haggard, 2015; Longo, Mattioni, & Ganea, 2015). Our data also showed similar but weaker magnitudes of the distortions on the palmer side in the finger task, consistent with previous findings (Longo & Haggard, 2012). These findings clearly replicate previous research and indicate the implicit hand images are reliably estimated in the current study.

Consistent with previous studies (Baron-Cohen et al., 2001; Wakabayashi et al., 2004; Wakabayashi et al., 2006; Wheelwright et al., 2006), higher AQ and SQ scores and lower EQ scores were observed for the male compared to female participants (Table S1B), and there were a positive relationship AQ and SQ scores (Spearman's Rho, finger: 0.24, $p = 0.01$; marker: 0.27, $p = 0.005$) and a negative relationship between AQ and EQ scores (finger: −0.60, $p < 0.001$; marker: −0.59, $p < 0.001$). Furthermore, the participants diagnosed with ASD showed higher AQ and EQ scores than the IQ-matched sample without a diagnosis. These findings indicate that the measurements of autistic traits are reliable in this study.

We did not observe any significant relationships between the distortions in implicit hand maps and the autistic traits. There were also no significant relationships between the autistic traits and within-individual variability in localization responses and implicit hand maps during the experiment. We further obtained congruent results in the comparison between the people with and without the diagnosis in the IQ-matched samples. These findings suggest that implicit body representations are not significantly affected by level of autistic traits.

A model has been proposed to explain somatoperceptual information processing through several steps (Longo, 2015; Longo et al., 2010; Tamè et al., 2019). In this model, proprioceptive sensations are combined with an internal representation of posture (the postural schema; e.g., relationships of joint angles) as well as canonical postural priors. Information about body postures is then integrated with representations containing metric properties of the body (a model of body size and shape) to provide an estimate of the location of the body in external space (spatial localization of body). The spatial location of touch on the body surface can be perceived by integrating locational information regarding the body in space and touches on the body surface (spatial localization of touch; e.g., a touch on my left hand located on the left side of space). The current study estimated the implicit hand map underlying position sense with proprioceptive sensation, where the processes of *spatial localization of the body* are mainly involved. In contrast, previous studies showing ASD-related characteristics in proprioceptive processing focused on the situations related to hand movements in the external space (Haswell et al., 2009), temporal order judgments on the hands with hands crossed (Wada et al., 2014), and illusory sensations in the external space with touch on the body surface (rubber hand illusion; Cascio, Foss-Feig, et al., 2012; Greenfield et al., 2015; Ide & Wada, 2017; Paton et al., 2012). These are clearly related to the processes of *spatial localization of touch*. Together with these findings, our findings suggest that perceptual processes related to *spatial localization of the body* are consistent across levels of autistic traits.

It has been assumed that brain areas related to somatosensory and motor processing such as the superior (e.g., Filimon et al., 2009; Graziano & Cooke, 2006; Pellijeff et al., 2006) and posterior (Sterzi et al., 1993; Vallar et al., 1993) parietal cortices and the lateral intraparietal areas (Fasold et al., 2008; Snyder et al., 1998) are involved in the processes of *spatial localization of body* (Longo et al., 2010). Anisotropy of tactile distance perception is reported to occur in a very similar manner with the distortions of implicit hand maps (Longo, 2015, 2022; Longo & Haggard, 2011), whereas it should be noted that independency of processes in implicit hand maps and tactile distance (Hidaka et al., 2020; Longo & Morcom, 2016). Interestingly, Longo and Golubova (2017) have demonstrated that the distortions of implicit hand map from the judgment of the perceived distance across different points of the hand. Using multidimensional scaling, they reconstructed the shape of the implicit hand map based on the relative relationships among the perceived distances between locations on the hand. By adopting the same technique for fMRI measurements, the distortions of implicit hand maps are observed in neural response distributions in the primary somatosensory (SI) and motor (M1) areas (Tamè et al., 2021). These findings imply that a lower level of neural processing could be involved in the processes of *spatial localization of the body*. In contrast, as described in the abovementioned model, the processes of *spatial localization of touch* taking posture into account have been assumed to need more perceptual and computational load (Yamamoto & Kitazawa, 2001) with a certain latency (around 180 ms; Azañón & Soto-Faraco, 2008a, 2008b). In addition to the superior and posterior parietal cortices, brain areas such as the ventral intraparietal area (Duhamel et al., 1998) and ventral premotor cortex (Graziano et al., 1994) are assumed to be involved in the processes of *spatial localization of touch* (Longo et al., 2010). Based on these previous findings and the findings of the current study, we could assume that relatively lower levels of somatosensory and motor neural processes are involved in implicit body representations with proprioceptive sensation similarly across levels of autistic traits. This idea seems to be consistent with the evidence that no differences between people with and without the diagnosis of ASD for the occurrence of a tactile illusion (cutaneous rabbit illusion) (Wada et al., 2020), in which the primary somatosensory cortex (SI) is involved (Blankenburg et al., 2006).

The current study demonstrated no significant relationships between autistic traits and the distortions in implicit hand maps underlying position sense. Our findings suggest the existence of common perceptual and neural processes for implicit body representations with proprioceptive sensations across levels of autistic traits. It should be noted that sensory characteristics related to ASD are variable even among individuals diagnosed with ASD (Kaneko et al., 2022; Wada et al., 2023). It has also been suggested that the structure of the components of the AQ may vary across populations (e.g., English et al., 2020) and that all individuals having AQ scores above a cut-off criterion do not always meet the clinical diagnosis of ASD (Ashwood et al., 2016). Also, it should also be notable that the AQ scores for females may be underestimated, as the understanding of ASD traits in females is still developing (Lockwood Estrin et al., 2021). Thus, future studies need to verify the validity of the findings of the current study with a larger number of participants including a more general population with greater variation in age and country and taking sex differences into consideration, together with an investigation of the structure of the components of the questionnaires that estimate autistic traits. Investigations of neural processes are also necessary for similarities in lower levels of proprioceptive sensation among differences in autistic traits. Given that the perceptual processes involved in spatial localization of the body are consistent, and that the processes of spatial localization of touch are different across levels of autistic traits, interventions that link these processes, such as training to localize touch to the body surfaces in external space and in a dynamic situation, may reduce irregularities in tactile localization including irregularities of motor performances (Cook, 2016) for people with higher levels of autistic traits. These investigations, together with the current findings, could contribute to a further understanding of commonalities and irregularities of perceptual and neural mechanisms for somatosensory and motor processing in people with the diagnosis of ASD or higher autistic traits.

ACKNOWLEDGMENTS

This research was supported by a Grant-in-Aid for Scientific Research (No. 17K00214) from Japan Society for the Promotion of Science to Souta Hidaka and Grants-in-Aid for Scientific Research (Nos. 19H04921, 20H04595, and 21H05053) from Japan Society for the Promotion of Science to Makoto Wada. The authors thank Dr. Misako Sano for assessment using ADOS-2, and Dr. Keiko Maida, Ms. Megumi Wada, and Ms. Wang Yichin for assessment using WAIS-III.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in OSF at https://osf.io/362ex/.

ETHICS STATEMENT

All procedures performed in the study were in accordance with the principles of the Declaration of Helsinki and were approved by the local ethics committees at Rikkyo University (Reference number: 19-44) and National Rehabilitation Center for Persons with Disabilities (Reference numbers: 31-98, 2020-011).

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How to cite this article: Hidaka, S., Chen, N., Ishii, N., Iketani, R., Suzuki, K., Longo, M. R., & Wada, M. (2023). No differences in implicit hand maps among different degrees of autistic traits. *Autism Research*, *16*(9), 1750–1764. https://doi.org/10.1002/aur.2979