RUNNING HEAD: BODY PARTS MODULATE TACTILE PERCEPTION IN EARLY CHILDHOOD

Part-based representations of the body in early childhood: Evidence from perceived distortions of tactile space across limb boundaries

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HIGHLIGHTS

1. Body part boundaries modulate perceived tactile distance from 5 years of age.
2. As in adulthood, 5- to 7-year-old children perceive tactile stimuli that cross over a body part boundary (the wrist), as further apart than two stimuli presented within the bounds of a body part.
3. We report the first observation in children of Weber's Illusion:
4. From 5 years of age, children perceive the distance between two points presented on the skin surface to be larger in regions of high tactile acuity (the palm) compared to those of low tactile acuity (the ventral forearm) (i.e., Weber's illusion).
5. We propose that a part-based (topological) body representation is particularly advantageous during early life given the constant change in the metric properties inherent in physical growth.

ABSTRACT

Studies show that touch in adults is referenced to a representation of the body that is structured topologically according to body parts; the perceived distance between two stimuli crossing over a body part boundary is elongated relative to the perceived distance between two stimuli presented within one body part category. Here we investigate this influence of body parts on tactile space perception in children of five, six and seven years of age. We presented children with pairs of tactile stimuli on the left hand/arm, either within the hand, within the forearm, or over the wrist. With their eyes closed children were asked to adjust the distance between the thumb and forefinger of their right hand to represent the felt distance between the two tactile stimuli. Like adults, the children perceived the distance between two stimuli that cross the body part boundary to be further apart than those that were presented within the hand or arm. They also perceive tactile distance to be greater on the hand than the arm which is the first observation of Weber's illusion in young children. We propose that a topological mode of body representation is particularly advantageous during early life given that body part categories remain constant while the metric proportions of the body change substantially as the child grows.

Body parts are a particularly salient category set during early childhood. Body part nouns are among the earliest words that infants learn, with evidence of comprehension as young as 6 months of age (Tincoff & Jusczyk, 2012). Body parts are also the focus of many early social interactions including songs and games (such as "Simon Says" and "Heads, Shoulder, Knees and Toes"), in which children are taught about the body as a collection of separable parts, with distinct labels and functional roles. Indeed, this structural breakdown of the body is seen throughout life in language (Enfield, Majid & Van Staden, 2006), semantics and action (Bermudez, 1998). It is also likely that body parts become more salient as a child's action repertoire develops. With the acquisition of skilled action the child begins to select and coordinate individual body parts for the appropriate tasks rather than employing a limb as a monolithic whole (Assaiante & Amblard, 1995; Berthier, Clifton, McCall & Robin, 1999). These emerging distinct functional roles of body parts (e.g., the arm as an extender, the hand as a grasper) may support the consolidation of perceptual body part categories, segmenting them according to their functional boundaries (the joints). Nonetheless, little is known about the development of part-based perceptual representations of the child's own body.

Converging neuropsychological studies (Buxbaum & Coslett, 2001; McGeogh & Ramachandran, 2011; Melzack, 1989, 1990; Ramachandran & Hirstein, 1998) suggest that adults have a representation of body structure, the Body Structural Description (Buxbaum & Coslett, 2001), which codes the body topologically, i.e., in terms of body parts and their adjacencies. It is thought that such part-based representations of the body in healthy adults lead to distortions of tactile space (de Vignemont, Tsakiris & Haggard, 2005; Le Cornu Knight, Longo & Bremner, 2014; Mancini, Longo, Iannetti & Haggard, 2011; Tsakiris, 2010; Tsakiris, Constantini &

Haggard, 2008). De Vignemont and colleagues (2009) report a perceptual elongation of distance between tactile stimuli presented over a body part boundary (the wrist), relative to those presented within one part (e.g., the hand). Reminiscent of the category boundary effect found in other sensory domains (e.g., Kay & Kempton, 1984), two stimuli presented on one body part are perceived to be more similar in location than they actually are (i.e., closer together) whereas those that fall on either side of the body part boundary are perceived to be more distinct (further apart).

Le Cornu Knight, Longo and Bremner (2014) tested an alternative possible interpretation of the tactile category boundary effect reported by De Vignemont et al. (2009). They considered whether the elongation of tactile distance over the wrist could result from Weber's illusion. Weber observed that perceived distance between tactile stimuli increases in line with increases in spatial acuity. Thus the perceived elongation over the wrist could be explained by a localized increase in acuity in that area (Cody et al., 2004). However, Le Cornu Knight et al. showed that the elongation of tactile distance only occurred in one direction, across the wrist, rather than both across and along the wrist boundary. This shows that the effect is specific to crossing the wrist boundary rather than the region of the wrist *per se*, and is therefore consistent with the proposal that a perceptual elongation of tactile distance over the wrist is due to a central part-based representation of body structure. No research has yet investigated the developmental origins of the influence of part-based representation of the body on tactile perception.

Developmental research into body representations has largely focused on what infants know about the bodies of others. Young infants appear to hold a basic representation of the typical human form, which continues to develop over infancy (Gliga & Dehaene-Lambertz, 2005; Heron & Slaughter, 2008; Heron-Delaney, Wirth

& Pascalis, 2011; Slaughter & Heron, 2004; Slaughter, Heron-Delaney & Christie, 2011). By nine months of age infants expect individual body parts to be attached to a whole body (Slaughter & Heron, 2011), and are sensitive to the relative proportions of body parts (Zieber, Bhatt, Hayden, Kangas, Collins & Bada, 2010). Such studies suggest that infants hold a basic model of the typical human form and the spatial relation between the parts. However they do not address how infants represent their own bodies.

Brownell, Nichols, Svetlova, Zerwas and Ramani (2010) investigated developing knowledge of the layout of own-body parts in 20- to 30-month-old children. In this study, participants were asked to place stickers on specified body parts, copying an experimenter, and to imitate meaningless gestures aimed at a specified site. Younger children were able to accurately locate two or three common body parts (e.g., hand and foot). By 30 months, children were able to locate almost twice as many body parts including less commonly defined sites (e.g., neck), but still did not perform at ceiling. Such findings have shown that there is a rudimentary knowledge of the layout of body parts by the second birthday. It remains unclear however, whether such knowledge of parts impacts on own-body perception as it does in adults (de Vignemont et al., 2009; Le Cornu Knight et al., 2014).

In the present study, we examined the extent to which body parts structure tactile perception in early childhood. We measured the modulatory effect of body part boundaries on tactile distance estimation in children aged five-to-seven years, adapting de Vignemont et al.'s (2009) tactile distance estimation task for this purpose. The body and limbs continue to grow rapidly in early childhood, accompanied by substantial developments in motor skills (Henderson, Sugden & Barnett, 2007). As these factors might potentially impact on the representation of body parts, we identified early childhood as a potentially fertile period for investigation. Through a process of piloting, it was apparent that five-year-olds were the youngest age group that could comply to task demands eliciting estimations of tactile distance. In this task participants are presented with tactile pairs in the proximodistal axis either within the hand or arm or crossing the wrist. Rather than asking children to estimate tactile distances with a verbal response (de Vignemont et al., 2009), which was deemed to difficult for these age groups, we asked them to adjust the distance between their thumb and forefinger to indicate their estimation. We expected that, like adults (de Vignemont et al., 2009; Le Cornu Knight et al., 2014), children would perceive tactile distances as greater when the stimuli crossed the wrist than if they remained within the arm or hand. We made this prediction given that a bias towards a representation of topological spatial relations is seen early in development in other spatial domains (Newcombe, Huttenlocher, Drummey & Wiley, 1998; Newcombe & Huttenlocher, 2000; Piaget and Inhelder, 1948). We also considered that topological representations of body structure are likely to be particularly valuable in early development given that, whilst the body is changing in size and proportion, the part-based relationships remain constant and therefore provide a stable basis for representing the body.

Method

Participants

Forty-eight typically developing children participated, in three age groups (5-, 6-, and 7-year-olds; see Table 1). All participants reported that they were right handed, and this was tested by asking them to write their name. All also had normal or corrected-to-normal vision. Three five-year-olds were excluded as they failed to complete the trials. Informed consent was obtained from all of the children's parents.

Experimental procedures were approved by the Department of Psychology Research Ethics Committee at Goldsmiths, University of London.

--Insert Table 1 about here--

Materials and design

Participants were seated at a table with their left arm resting on a table, palm up and outstretched (Fig. 1). A black screen (30 x 30 cm) was placed immediately to the right of the participant's left arm in order to obscure that arm and the stimuli from view. Participants were asked to estimate the distance between two tactile stimuli presented to the left forearm and hand. Stimuli were delivered using two plastic pins with blunt but well-defined ends (approx. 1 mm diameter) attached to a ruler at separations of 15 mm ("Short"), 35 mm ("Medium") and 55 mm ("Long"). These distances are somewhat shorter than those used by de Vignemont et al. (2009) in order to account for the smaller hands of the child participants. The participant's right hand rested comfortably in front of them on the table, with the thumb and forefinger placed on a long strip of graph paper extending away from the body. The experimenter use the graph paper to record the participants' responses.

--Insert Figure 1 about here--

On each trial, a tactile pair was presented to the ventral surface of the left forearm/hand in a proximodistal orientation (i.e., along the length of the forearm/hand). Each tactile pair was centred around a predefined presentation point on one of three body parts (Hand, Wrist and Forearm; see Fig. 2).

--Insert Figure 2 about here--

Across trials, tactile pairs of three varying Distances (short, medium, long), were presented on each of the three Body parts (Hand, Wrist, Forearm), yielding nine unique trials. Each of these nine trial types was presented 3 times, in a pseudorandom order that was varied between participants. Thus, participants completed 27 trials in total. Raw distance estimates for each trial were plotted against the actual tactile distances presented across Distance and Body Part conditions, yielding a regression line for each participant from which R^2 and y-intercept values were calculated. R^2 values for each participant thus provided a measure of their overall discriminative sensitivity. And y-intercepts provided an overall measure of bias in their estimates (with positive values indicating over-estimation, and negative values underestimation). These overall measures of discriminative sensitivity (R^2) and bias (y-intercept) in participants' tactile distance estimates were compared across age groups using univariate analysis of variance (ANOVA). Judgment error scores were next calculated for each participant for each condition by subtracting the actual distance presented from the estimated distance for each trial. Therefore these judgment error scores provided an index of distortions of perceived tactile distance relative to the veridical. Positive judgment errors represented an overestimation, and negative errors represented an underestimation of distance. As we were not interested in children's estimation of different distances, we collapsed scores across Distance conditions for judgment error analysis. Judgment errors were thus entered into a mixed 3 x 3 ANOVA (Body part x Age group).

Procedure

The participants were asked to keep their eyes closed during testing and the experimenter monitored this throughout. As already mentioned, an occluding screen was also in place to prevent the participants seeing their left arm or the tactile pairs between trials. On each trial the participants were presented with two simultaneous tactile stimuli which were separated in the proximodistal axis along the ventral forearm/hand. The experimenter was careful to apply equal pressure across the pins and across trials. The participants were asked to adjust their thumb and forefinger to represent the felt distance between the stimuli. The children were asked to say "ready" once they had decided upon finger positioning, at which point the experimenter terminated stimulation and marked the response at the tip of each finger on a strip of graph paper. Prior to the experimental trials, the participants received five practice trials, with feedback, in which they were allowed to see their response hand but not the stimulated one. During this time, the pressure of the tactile stimuli was discussed with the participant to ensure that it was firm but not uncomfortable.

Results

Discriminative sensitivity and bias in children's estimations of tactile distance

In order to determine whether the participants were able to differentiate between the tactile distances presented, raw distance estimates for each trial were plotted against the actual tactile distances presented across conditions, yielding a regression line for each participant from which R^2 was calculated (see Table 2). We first compared the R^2 of children's distance estimates against zero (no discrimination) separately for each age group with one-sample t-tests. All age groups demonstrated an R^2 which was reliably greater than zero (see Table 2), indicating their ability to discriminate tactile distances. We next examined whether these R^2 values differed across age groups using a one way ANOVA, which revealed no reliable differences, $F(2, 42) = 0.04$, n.s., $\eta^2_p = .002$.

--Insert Table 2 about here--

In order to determine whether participants in each age group reliably under- or over-estimated the tactile distances presented to them, we calculated the y-intercept of each participant's regression line of actual against estimated tactile distance. One-sample t-tests, of the means of these y-intercept values against zero confirmed that participants in all age groups significantly over-estimated tactile distance (indicated by positive y-intercept scores; see Table 2). We next examined whether these y-intercept values differed across age groups using a one-way ANOVA, which revealed no reliable differences, $F(2, 42) = 0.89$, n.s., $\eta^2_p = .04$.

Judgment error scores

The dependent variable of particular interest in this investigation was judgment error (estimated tactile distance – actual distance; see Fig. 3). This measure allows us to examine the pattern of over- or under-estimation of perceived tactile distances across body parts and age groups. Positive errors represent an overestimation of distance, and negative errors an underestimation. Judgment error scores (collapsed across Distance conditions) were entered into a 3 (Body part: Hand, Wrist, Forearm) x 3 (Age group: 5-, 6-, 7-year-olds) mixed ANOVA. We found a main effect of Body part, $F(2, 84) = 28.0$, $p < .001$, $\eta^2_p = .40$. Post-hoc t-tests using bonferroni correction ($\alpha = .017$) showed that this effect was driven by: i) the distance at the hand ($M = 3.23$, $SD = 7.88$) being significantly overestimated relative to the arm ($M = 0.66$, $SD = 8.46$), $t(44) = 4.2$, $p < .001$, $d_z = .62$, and ii) the distance at the Wrist ($M = 5.74$, $SD = 8.46$) being significantly overestimated relative to both the Forearm and the Hand [Forearm: $t(44) = 7.1$, $p < .001$, $d_z = 1.06$; Hand: $t(44) = 3.8$, $p < .001$, $d_z = 0.57$]. Greater perceived tactile distance on the hand than the arm is also seen in adults (e.g., Le Cornu Knight et al., 2014), and is taken as an example of Weber's illusion (1834/1996; see also Green, 1982; Longo & Haggard, 2011). The current findings represent the first demonstration, as far as we are aware, that Weber's illusion is also a phenomenon of early childhood. Most pertinent to the current investigation however is the overestimation at the wrist relative to both arm and hand, which indicates that children between 5 and 7 years demonstrate an elongation of perceived tactile space over the wrist. This finding is indicative that body part boundaries modulate perceived tactile distance in children, as has been observed in adults (de Vignemont et al., 2009; Le Cornu Knight et al., 2014).

--Insert Figure 3 about here--

There was no significant main effect of Age group, $F(2, 42) = 2.2$, n.s., $\eta^2_p = .10$, and no interaction of Body part and Age group ($F < .1$). An additional variable was computed, to represent the size of the categorical effect; i.e., the overestimation at the wrist relative to the hand and arm. This variable was the mean of all judgment error scores for distances presented to the Hand and Forearm, subtracted from the mean error scores from stimuli presented across the Wrist. A one-way ANOVA comparing this categorical effect variable between the Age groups revealed no main effect of Age group, $F(2, 42) = 0.3$, n.s., $\eta^2_p = .002$.

Discussion

In adults, anatomical landmarks such as the wrist have a structuring effect on tactile distance estimation (de Vignemont et al., 2009; Le Cornu Knight, Longo & Bremner, 2014), as well as tactile localisation tasks (Flach & Haggard, 2006). On the basis of such findings it is argued that touch is automatically referenced to a high-level topologically structured body representation (de Vignemont, Ehrsson & Haggard, 2005; Mancini et al., 2011), and that one outcome of this process is a resultant structuring of tactile perception; two points that are presented within the bounds of one body part are perceived as more similar and therefore closer together than those presented across a body part boundary. Here, we report the same perceptual distortion in children of 5 to 7 years of age.

We have also demonstrated that, as in adults (e.g., Le Cornu Knight et al., 2014), elongations of perceived tactile distance relative to the veridical are greater on the hand than on the arm in 5- to 7-year-olds. This particular distortion is readily explained by Weber's illusion (1834/1996), in which perceived distance systematically increases in parallel with increases in the tactile acuity of a given skin region (Cholewiak, 1999; Green, 1982; Longo & Haggard, 2011). As far as we know, this is the first reported observation of Weber’s illusion in early childhood. Weber’s illusion as measured by our task appears to be constant across the ages of 5 to 7 years, and reasonably comparable to the size of such effects in adults (e.g., de Vignemont et al., 2009). In line with interpretations of Weber’s illusion in adults (Longo & Haggard, 2011; Taylor-Clarke, Jacobsen, & Haggard, 2004), we propose that the greater receptor density, and thus spatial acuity, in the skin of the hand than in the skin of the arm is what drives the differences in bias in tactile distance estimates in these body parts. In order to achieve tactile size constancy across physiological differences in acuity, adults at least partially compensate for such variations in tactile receptor density via reference to other spatial sense modalities (e.g., vision; Taylor-Clarke et al., 2004). It may therefore be interesting for future studies to investigate the origins of tactile size constancy in early life. Here, we have observed an adult-like Weber’s illusion at 5 years of age. It is possible that developmental reductions in Weber’s illusion may be observed prior to this age, before the child has learned to integrate the sense of vision and touch sufficiently (e.g., see Begum Ali, Spence & Bremner, 2015; Rigato, Begum Ali, Van Velzen & Bremner, 2014).

The presence of Weber’s illusion in children brings us to an alternative account of the observed elongation of tactile distance over the body part boundary which we must address. Elongation of tactile distance over the wrist could be explained by Weber’s illusion if there is enhanced acuity at the wrist (Cody et al., 2008), as this would lead to an increase in perceived distance. Le Cornu Knight, Longo and Bremner (2014) have ruled out such an interpretation of the tactile wrist boundary effect in adults, showing that tactile elongation is only observed across the wrist boundary, and not along it. Elongation in both directions would be predicted by the account based on localized acuity and Weber's illusion. To date, no studies comparing tactile acuity along and across the wrist have been carried out in developing populations. Whilst it is therefore possible that the perceived elongation of distance reported here might be explained by localized increases in acuity at the wrist in children, given the similarity between our findings and those reported in adults (e.g. de Vignemont et al., 2009), we assert that our findings are by far the best interpreted in terms of an influence of the body part boundary on tactile perception.

There are a range of ways in which it is possible to represent the body spatially. Here we have appealed to a part-based (or topological) mode of representing tactile distance on the body surface in childhood as has been found in adults. This form of spatial representation is described elsewhere in the context of spatial processing more broadly. For instance it is well known that both coordinate-based (metric) and categorical (topological) spatial codes are used in object recognition (Jager & Postma, 2003; Kosslyn et al., 1989). It has been suggested that categorical encoding may provide a particular advantage when representing flexible shapes that undergo contortions (Laeng, Shah & Kosslyn, 1999). The body is an example of just such a flexible shape; the metric relations between limbs and trunk shift continually across changes in body posture whereas the topological relations between parts remain constant.

The precedence in early development of topological modes of representing space has been remarked upon in discussions of a number of domains of spatial cognitive development. Piaget and Inhelder (1948) argue for a qualitative shift from categorical (topological) to coordinate based (metric) representations of space in middle childhood. More recently, others have demonstrated that both metric and topological modes of spatial representation are available much earlier than Piaget and Inhelder proposed (e.g., Newcombe et al., 2005), but nonetheless provide evidence of shifts in the weighting of topological to metric representations in early life (Newcombe et al.,1998; Newcombe & Huttenlocher, 2000). Here we argue that a similar process occurs in bodily representation. Importantly however, we must appeal to some mixture of topological and metric representational codes in interpreting our findings. We have clearly shown the influence of body parts on tactile distance estimates, but the precision of the children's estimates within body parts (i.e., in the hand and arm conditions) is such that some ability to represent tactile distance metrically is clearly apparent. What we propose is that whilst a range of spatial codes are at play in young children's body representations, there is a particular weighting towards a topological code in early life.

The presence of a robust topological body representation may be of particular utility in early childhood. Representing the body metrically through childhood is likely to be difficult given the rapid physical growth from birth to adolescence which occurs differentially across the body, and is time-locked to specific body parts. Hands, for example, reach near adult size in late primary-school age, whereas arms experience a growth spurt much later in adolescence (Tanner, 1990). Whilst the size and relative proportions of the body change across development the topological relationships between body parts remain constant, providing a stable basis for body representation. A further argument for the importance of part-based representations of the body in early life is that such representations might provide a more practical basis for mapping one's own body parts onto those of others in observing, learning and refining actions. A growing body of research suggests that infants and children map their own motor responses to the observed actions of others (e.g., Marshall & Meltzoff, 2014; Southgate, 2013). Given the substantial differences in the metrics of adult and child bodies, we propose that any process in which children map their actions to those of adults (see Naish, Houston-Price, Bremner & Holmes, 2014), must be related to body parts. In other words, body parts provide the common basis for shared representation of the body and action in early life.

We have demonstrated the influence of a part-based body representation on tactile space perception by 5 years of age, but questions remain concerning the developmental origins of such categories. One interesting avenue for future research concerns the possible role of language. Enfield et al. (2006) suggest that it is through language that we learn to delineate the body in a culturally meaningful manner, and language development plays an important role in category-set construction (McDonough, Choi & Mandler, 2003). Furthermore, there is ongoing lively debate concerning the role of language in structuring categorical perception (Bornstein, Kessen & Weiskopf, 1976; Franklin & Davies, 2004; Kay & Kempton, 1984; Whorf & Carroll, 1964; Winawer, Witthoff, Frank, Wu & Wade, 2007). Although it is important to note that the phenomenon we have reported here does not meet the strict definition of categorical perception similar linguistic effects might also be observed in this context. In certain languages (such as Croatian and Indonesian), 'hand' and 'arm' are referred to by the same term. It would be interesting to test whether these languages show such a strong category boundary effect and thus further elucidate the role of language in structuring body representations and categorical representations in general.

Finally, on inspecting the children's performance at tactile distance estimation in the current experiment more generally, it is interesting to note that all of the age groups of children overestimated tactile distance on average. In contrast, de Vignemont et al. (2009) found that adults consistently underestimate the distance between two tactile points (a phenomenon known as tactile spatial compression; Green, 1982). One possible explanation for the reduction in perceived tactile distance between 7 years and adulthood could be that tactile distance is coded relative to some bodily metric (such as body or body part size), as is seen for instance in the visual perception of obstacles (Warren & Whang, 1987; Pufall & Dunbar, 1992). Indeed, if at all ages tactile distance was coded in relation to body part size (Taylor-Clarke et al., 2004) this would predict an increase in tactile spatial compression as the body grows.

In childhood, as in adulthood, a body parts and their boundaries modulate tactile perception. We have argued that body part boundaries (in this case the wrist) give the impression that stimulus pairs crossing the boundary are perceptually more distinct, leading to an overestimation of tactile distances across the category boundary (de Vignemont et al., 2009). We suggest that in early childhood it may be particularly advantageous to bias a representation of the body towards a topological code comprising its constant parts. Here we observe that topological effects on tactile representations are present and analogous between the ages of five and seven, whereas metric representations may well be constantly adjusting in response to physical growth. Further research, perhaps in human infancy, is required to determine the origins of the structuring effect of body parts on tactile spatial perception, whether there are particular experiential drivers of topological representations of the body, or alternatively whether they arise independently of experience (McGeogh & Ramachandran, 2011).

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TABLES

Age group	*n*	*Gender split*	*Mean age in months*	*SD of age in months*
5-year-olds	15	8m, 7f	67.9 months	2.6 months
6-year-olds	15	6m, 9f	77.3 months	3.5 months
7-year-olds	15	7m, 8f	89.0 months	4.2 months

Table 1: Participant characteristics

	R^2				y-intercept			
Age group	*Mean (SD)*	*t* (d.f.)	*p*	d_z	*Mean (SD)*	*t* (d.f.)	*p*	d_z
5-year-olds	.42 (.16)	10.0 (14)	<.001	2.6	25.11 (6.42)	15.2 (14)	<.001	3.9
6-year-olds	.43 (.19)	8.7 (14)	<.001	2.3	21.55 (9.97)	8.4 (14)	<.001	2.2
7-year-olds	.41 (.18)	8.7 (14)	<.001	2.2	23.89 (4.93)	18.8 (14)	<.001	4.8

Table 2: Mean R2 and y-intercept values for regression lines of actual against estimated tactile distance plotted for each participant, compared across age groups. These provide measures of the discriminative accuracy and bias of participants tactile distance estimates. One-sample t-tests are reported in which R2 and y-intercept values are compared against zero. Zero acts as a baseline level of performance for the R2 (discriminative accuracy) measure, and as veridical performance for the y-intercept (bias) measure.

FIGURE CAPTIONS

Figure 1: A schematic depiction of the experimental set up; the participant's left arm, to which the tactile stimuli were presented was outstretched with palm up on a table (a). A black board (c) obscured vision of the left arm and hand. The right arm (b) made estimates of the tactile distances presented to the left arm and hand by adjusting the distance between thumb and forefinger against a strip of graph paper (d) which was marked by the experimenter.

Figure 2: The central presentation points, around which the tactile distances were presented are depicted as black circles. All presentation points were central in the mediolateral axis (the axis running across the length of the arm). The wrist presentation point (A) was predefined as the distinct skin crease at the narrowing between the ulna bone and the hand. The hand presentation point (B) was predefined as the point halfway between the line of the wrist and the bottom of the middle finger. The arm presentation point (C) was predefined as a point measured on the ventral forearm at an equal distance from the wrist as the hand presentation point.

Figure 3: Group mean judgment errors (estimated tactile distance - presented distance) in mm (y-axis), for all age groups (5-, 6-, and 7-year-olds) collapsed across tactile distances, for all body part locations (Arm, Wrist, Hand along the x-axis).

Figure 1

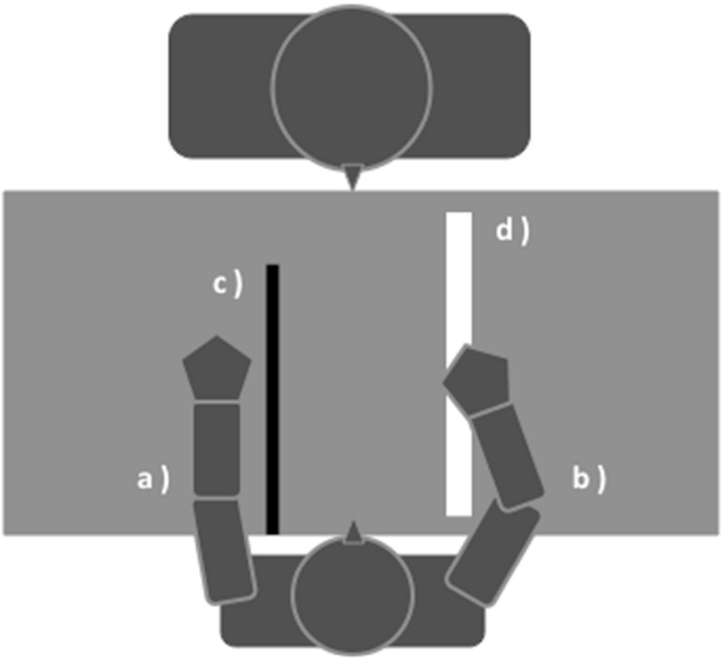


Figure 2

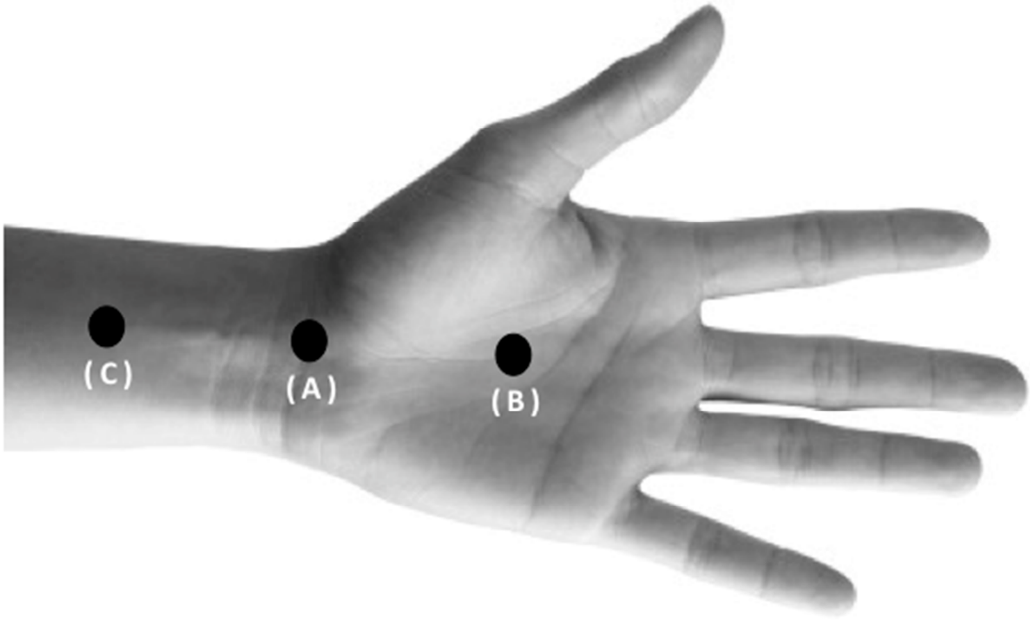
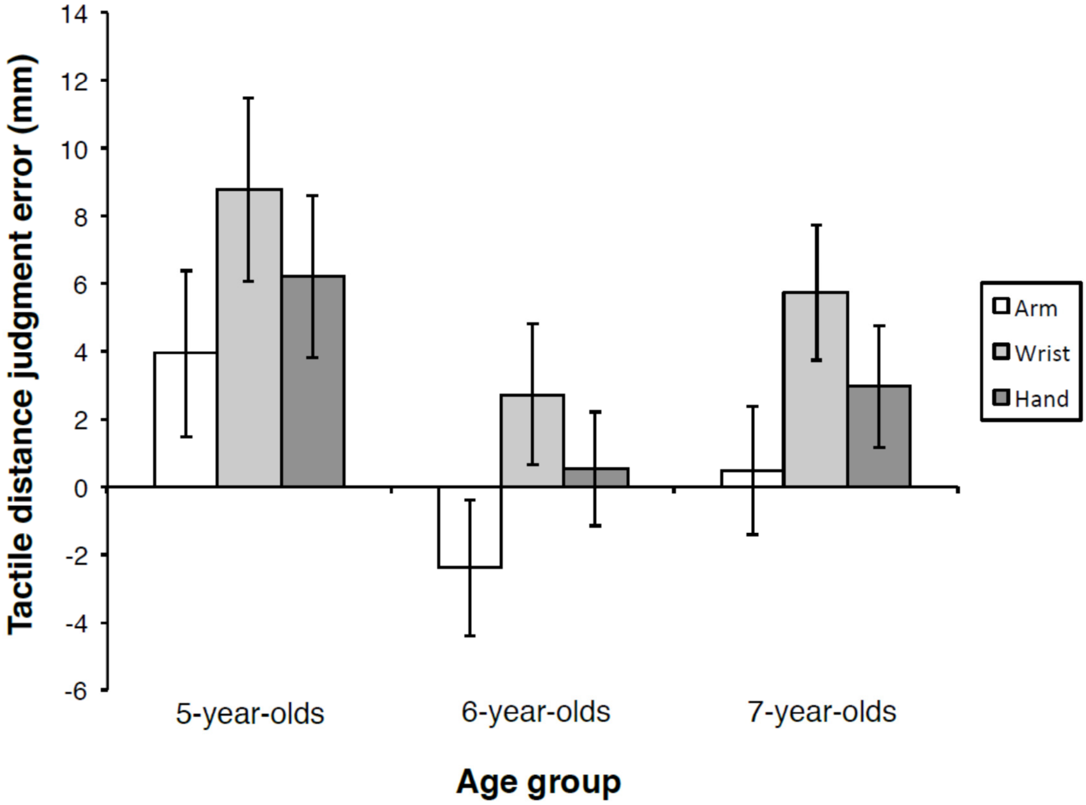


Figure 3


Tactile distance judgment error (mm)
14
12
10
8
6
4
2
0
-2
-4
-6
5-year-olds
6-year-olds
7-year-olds
Age group
Arm
Wrist
Hand