



## A lifespan study on body schema and perceived reaching distance

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### ABSTRACT

The plasticity of body representation in response to tool use is a dynamic process that evolves across the lifespan. Research has shown that tools can become integrated into the body representation, effectively being treated as extensions of the body. However, this incorporation is age-dependent, reflecting the ongoing development, stabilization, and potential decline of sensorimotor integration and body representation mechanisms. In this study, we explored how age influences the plasticity of the body schema and perceived reaching distance during short-term tool-use training within near and far space. Eighty-four participants spanning various age groups (12–80 years old) participated in two experimental sessions, utilizing a well-established tool-use paradigm to manipulate objects within both near and far spaces. To assess changes in body schema, a tactile distance judgment test was administered on the forearm in the proximodistal orientation. Furthermore, we employed a reaching distance estimation task to evaluate perceived reaching distance prior and after tool-use training. Across all age groups, participants showed reduced distance estimation between tactile stimuli on the forearm, but tool-use training did not produce any significant changes in these judgments. Findings further revealed no significant changes in perceived reaching distance after tool-use training over either near or far distances. We conclude that, although a large body of prior literature reports tool-use effects on body representational plasticity, our findings indicate that short-term tool-use does not significantly alter tactile distance perception of the forearm or perceived reaching distance across age groups. This suggests that brief tool-use exposure may be insufficient to induce lasting sensorimotor adaptations, and that more prolonged or immersive training may be required. While tool-use proficiency improves with age, the fundamental integration of tools into body representation appears to remain stable across the lifespan.

### 1. Introduction

As humans we have developed a remarkable ability to create and use tools that extend the capabilities of our bodies. This ability to design and use tools in flexible and innovative ways is widely regarded as a distinctive trait of *Homo sapiens*, setting us apart from most other species (Sanz et al., 2013; Shumaker et al., 2011). Tool-use has allowed us to extend the physical and cognitive boundaries of our abilities, making our daily lives more manageable and efficient (Vaesen, 2012; Baber, 2006). The impact of using tools extends to how we perceive and interact with our environment, whether physical or virtual, and how we perceive our own bodies' size, location and so on (Cardinali et al., 2011, 2012; Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009; Jahanian Najafabadi et al., 2023a, 2023b; Miller et al., 2014, 2017).

Body schema has been described as the internal representation of one's body in space that can be updated and reshaped, reflecting its dynamic nature which is evident even in infancy. These ongoing updates help form an internal, largely unconscious map of the body's position and structure (Assaiante et al., 2014). This notion is also supported by electrophysiological studies, such as Ronga et al. (2021), which suggest the presence of multisensory integration in newborns (18–92 h old) by using electroencephalography recording. The different pattern responses of the newborns to tactile and auditory stimuli, depending on the distance of the stimuli from the body, can be indicative of the presence of a boundary between their body space and the environment.

The dynamic nature of the body schema will continue even after the infancy period and continue to develop until after adolescence (Martel et al., 2021). Although age-related changes in body schema have been widely studied, findings remain inconclusive regarding the extent to

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which age determines patterns of body schema development and its susceptibility to modulation through sensorimotor training (e.g., active tool-use). Some variations in body schema update patterns can be found, especially during puberty (Martel et al., 2021), as our body goes through drastic length changes, and after the prolonged tool-use in different age groups such as young adulthood (Jahanian Najafabadi et al., 2023a). As noted in our previous study (Jahanian Najafabadi et al., 2023b), which was conducted in an augmented reality setting with older adults, despite their tool-use proficiency being comparable to that of younger adults (Jahanian Najafabadi et al., 2023a), no body schema plasticity was observed. These results give rise to the question of whether body schema plasticity is even necessary for sensorimotor learning or whether the stability of body schema in the senior population is because they can achieve the required level of sensorimotor proficiency by calling for an old sensory association without the need for building a new one. If the latter is the case, we shall see no training effects (comparing the first and last block of tool-use training) nor body representation updates after the tool-use paradigm within an old adult sample or in the case of using familiar tools with participants within other age groups (Martel et al., 2021). Using familiar tools might allow the older brain to rely on old sensory associations to achieve proficiency, thus bypassing the need for metric body schema plasticity. However, we can observe the fixed body schema in older adults despite the same strength of practice effect as young adults' sample in our previous study within augmented reality setting (Jahanian Najafabadi et al., 2023a, 2023b) or physical tools (Bahmad et al., 2020; Costello et al., 2015; Costello & Bloesch, 2017). Bahmad et al. (2020) reported that older adults show reduced offline proprioceptive recalibration but preserved online proprioceptive updating during tool-use. Despite this, their kinematic adaptations match younger adults, suggesting that internal body models are still updated, though mainly through immediate sensory feedback. Tool-induced plasticity therefore remains present in aging but relies on different mechanisms. Altogether, the body schema flexibility can be influenced by multiple factors like age, how familiar we are with the tool, how similar it is to our own body parts, and how well it serves its purpose (Cardinali et al., 2016; Cardinali et al., 2021; Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009; Miller et al., 2014; Sposito et al., 2012).

### 1.1. Tool-use in human development and across the lifespan

Over the past few decades, experimental studies have used different variations of the tool-use paradigm to explore the effect of using various tools such as computer's mouse and rake on the update of the body and spatial representation in humans (Canzoneri et al., 2013), and animals (Iriki et al., 1996; Maravita & Iriki, 2004). Recent research indicated that tools not only help manipulate the environment but also influence brain development by reshaping our body schema and peripersonal space (Inoue et al., 2001; Tomasino et al., 2012).

Successful tool-use relies on well-developed cognitive abilities, particularly the construction and updating of body representation as we age. Accurate mental models of the body and surrounding space are essential for handling tools because they allow individuals to estimate properties such as size, weight, and reach. Given the significant age-related changes in brain structure and function, it is crucial to understand how these changes influence tool-related body representations across development. Developmental research shows that these representations do not mature uniformly across the lifespan. Martel et al. (2021) reported that adolescents show delayed adoption of adult-like kinematic patterns during tool-use, likely due to immature motor control, limited multisensory integration, and rapid physical changes occurring before and during puberty. This delay reflects a gradual refinement of sensorimotor integration and body representation mechanisms. Proprioceptive integration with visual and vestibular inputs also develops progressively and is affected by the growth spurt during adolescence (Cignetti et al., 2013; Viel et al., 2009). Compared to adults,

adolescents tend to rely more heavily on visual cues than proprioceptive feedback when controlling posture and using tools (Assaiante et al., 2014; Martel et al., 2019; Cardinali et al., 2016). In contrast, older adults show reduced plasticity in body schema alongside heightened interoceptive sensitivity, suggesting that increased awareness of internal bodily signals may be negatively associated with body schema adaptability as age advances (Raimo et al., 2021).

There is evidence of a slow and U-shaped developmental trajectory in tool incorporation during puberty, with a shift towards an adult-like pattern only when body size stabilizes (Martel et al., 2021). Although Martel et al. (2021) demonstrated this trajectory by studying children and adolescents with a mean age of approximately 14 years, the broader developmental course of plasticity in tool incorporation across the full lifespan remains unclear due to the scarcity of studies involving all age groups (e.g., Bassolino et al., 2022).

Few studies have explored how age influences changes in body schema related to tool-use across different age groups, highlighting gaps in understanding the effects of age on these processes (For review: Bahmad et al., 2020; Costello et al., 2015; Costello & Bloesch, 2017; Jahanian Najafabadi et al., 2023a, 2023b; Jahanian-Najafabadi et al., 2025; Witt, 2021). However, to date, no study has systematically examined how body schema plasticity evolves across the lifespan, particularly in relation to its interaction with spatial representation during tool-use. Gaining insight into these lifelong changes is crucial, as body representation involves complex processes that require carefully controlled experiments and ecologically valid conditions.

To our knowledge, this is the first study to take wide range of age to investigating the plasticity of body representation, that is, how key components such as body schema and the perception of space (i.e., perceived reaching distance) within and beyond arm's reach evolve with age. We explored these variations through active tool-use training in both near and far spatial contexts. By including participants aged 12 years and older, we captured key developmental stages characterized by substantial physical and cognitive changes. To capture the distinct aspects of body representation in our measurements, we used a tactile distance judgment (TDJ) task to evaluate plasticity of body representation along with applying a reaching distance estimation (RDE) task for the evaluation of the perceived reaching distance relative to participants' arm's length before and after tool-use training.

### 1.2. Tactile distance judgment test as a measurement of body schema during tool-use

To investigate how forearm body representational plasticity changes following tool-use, researchers have employed TDJ as a metric (Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009; de Vignemont et al., 2005; Jahanian Najafabadi et al., 2023a, 2023b; Jahanian Najafabadi & Godde, 2025; Miller et al., 2014, 2017). TDJ assesses participants' ability to accurately perceive and judge the distance between a pair of tactile stimuli applied to the skin. By measuring TDJ before and after tool-use sessions, researchers evaluated how tool-use influences body schema. This approach has been instrumental in understanding how perceived tactile distance on the forearm/hand adapt to include tools and how these changes manifest in tactile distance perception.

Earlier studies (Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009; de Vignemont et al., 2005) proposed a link between tactile distance perception on specific body parts and changes in body schema. Subsequent research demonstrated that tool-use in younger adults can modify mental body representations, expanding the body schema to incorporate the tool itself (Jahanian Najafabadi et al., 2023a; Sun & Tang, 2019). Therefore, the accuracy of TDJ performance on the relevant body part may serve as a reliable marker of representational plasticity induced by tool-use.

Perceiving the size of objects touching the skin depends on an implicit representation of body form (Longo, Azañón, & Haggard, 2009).

Accordingly, if tool-use leads to representational plasticity, we would expect to see changes in the perceived size of objects contacting the skin surface. The ability to judge tactile distances is closely tied to the interaction between proprioception, body size, and body schema, as these factors collectively shape how the brain represents the skin's surface and spatial relationships on the body (Romano et al., 2018). Body size awareness plays a crucial role in accurately perceiving the distance between two tactile stimuli on the skin integrating sensory inputs, including proprioception, to form a coherent mental image of our body, essential for precise TDJ (Cardinali et al., 2016). In our recent study, we demonstrated that practicing with virtual tools in augmented reality can indeed alter body schema, resulting in reduced errors in TDJ estimations for stimuli aligned with the arm axis (Jahanian Najafabadi et al., 2023a).

### 1.3. Reaching distance estimation task as a measurement for perception of reaching space

Peripersonal space is not a static entity with a clear boundary, but rather a dynamic continuum that gradually shifts with distance (Longo & Lourenco, 2006; Di Pellegrino and Làdavas, 2014; Serino, 2019; Noel et al., 2018). Tools play a crucial role in shaping peripersonal space by influencing how individuals perceive affordances and by remapping bodily space (Sykes, 2023). Active tool-use has been shown to extend peripersonal space, as evidenced by visuo-tactile cross modal congruency tasks, and to update body representation, as indicated by reductions in TDJ responses (Vittersø et al., 2019).

To enrich this brief overview of studies and tasks aimed at evaluating the effect of active tool-use on peripersonal space remodulation, it is essential to mention the review and re-analysis by Holmes (Holmes, 2012; Holmes et al., 2020). In their work, key measurements for updating peripersonal space representation, including neuro-physiological, neuro-psychological, and behavioral indices, were reviewed and critiqued. This study provides one of the most substantial reassessments of evidence supporting tool-induced expansion of peripersonal space. Holmes (2012) argued that, depending on the spatial location of visual stimuli, different mechanisms may underlie tool-related changes in personal space representation, such as extension, projection, or addition. Moreover, the author highlighted substantial methodological limitations in earlier studies and emphasized that even when multisensory spatial interactions were observed through cross-modal congruency tasks, these effects were often weak. The author therefore cautioned that such findings should be interpreted carefully, as they may simply align with prevailing assumptions in the literature rather than provide definitive evidence for peripersonal space extension. This led to the suggestion that behavioral tasks like the cross-modal congruency paradigm may not directly capture peripersonal space updating and could instead reflect broader multisensory spatial representations associated with different reference frames around distinct body parts.

Together, this body of research highlights that tool-use can actively reshape both spatial perception and body representation, driven by sensorimotor engagement. This remapping process reflects the brain's capacity to flexibly adapt its internal models of the body and its spatial boundaries in response to action and interaction.

### 1.4. Current study

In this study, we investigated the effect of tool-use training on forearm representational plasticity associated with the perceived reaching distance using TDJ and a RDE task (Bourgeois et al., 2014; D'Angelo et al., 2018; Jahanian Najafabadi & Godde, 2025; Witt et al., 2005). Participants' age range 12 to 80 were trained with two different tools of varying sizes, and their forearm tactile distance perception, and reaching distance estimation were measured before and after each training block. The study's outcomes are expected to provide valuable insights into the forearm representational plasticity and perceived

distance modulations across the lifespan. The study design aimed to address key research gaps by exploring answers to three main questions besides testing the reproducibility of the previous studies within the lifespan context of our study. Our **first** question was whether perceived forearm tactile and reaching distances are age-dependent (baseline differences). **Secondly**, we tested whether different tool sizes lead to changes in the arm representation of the right hand wielding the tool, and **third**, we examined whether there is an interactive age-dependent effect between changes in forearm tactile distance perception and perceived reaching representations. We sought to understand if tool-use-induced representational plasticity measure via TDJ is age-dependent and varies based on the distance required to grasp an object (near vs far space). This question is particularly important given the significant changes in the human body and its representation over time, including years to achieve stable metric configuration and later sensorimotor declines.

## 2. Methods and procedures

### 2.1. Participants

In total, 84 healthy right-handed participants took part in the study (see Table 1 for demographic details), recruited across four distinct age groups. The sample size was chosen based on comparable work (e.g., Bahmad et al., 2020; Miller et al., 2014) and designed to ensure sufficient statistical power for both within- and between-group comparisons. An a priori power analysis using G\*Power for a one-way ANOVA (four groups,  $\alpha = 0.05$ ) indicated that  $N \geq 76$  would be adequate to detect medium effects typical in the embodiment literature ( $f = 0.25$ ). All participants had normal or corrected-to-normal vision, reported no history of neurological disorders, and were right-handed to ensure consistency with existing research protocols. Informed consent was obtained from all participants and, where applicable, from parents or legal guardians prior to participation. Participants were not informed about the study's hypothesis or potential errors to prevent bias and received age-appropriate compensation, either in the form of monetary payment or a gift (e.g., a book).

### 2.2. Study design

In this study, data collection and experimental procedures were divided into two separate sessions. The order of training blocks was counterbalanced across participants: each individual began with either the short-tool or the long-tool training session, assigned randomly to control for order effects. The initial session encompassed gathering demographic information and administering assessments for RDE and TDJ. Following this, participants engaged in five blocks of tool-use training (each 12-trials), where they used either a 30 cm, or 70 cm mechanical grabber to reach 60 objects at 80 cm and 120 cm, respectively. After each training block, participants were asked to rate a questionnaire including 12 questions about sense of ownership and sense of agency. A 45-min break was then provided before the commencement of the second tool-use training session.

In the second tool-use training session, a pre-test involving RDE and TDJ tasks from the same participants was conducted. The second session's trials mirrored those of the first session, except that in this session participants used a mechanical grabber of a size not used in the first

**Table 1**  
Participant demographic.

Age groups	Participation number	Age range	Mean age (SD)
Adolescents	19	12–17	15 (1.94)
Young adults	26	18–34	24 (3.42)
Mid-age adults	20	35–60	42 (5.38)
Older adults	18	61–80	66 (5.46)

session. During the continuation of 5 blocks of trials, post-test evaluations were conducted in the same way as the first session's post-test assessments, including TDJ and an RDE task along with a questionnaire for perceived sense of agency and ownership (Kalckert & Ehrsson, 2012, 2014; Zhang & Hommel, 2015). Details of the experimental design for both training sessions are presented in Fig. 1. As the focus of this research is solely on the investigation of tool-use induced representational plasticity and perceived reaching distance across the lifespan, we omitted the findings of perceived sense of agency and ownership and that has been reported in another publication.

### 2.3. Active tool-use training

During tool-use training, participants were instructed to fully stretch and extend their arm (and the tool) and grasp the objects that were set down on the table in front of them by using the grabber they held in their right hand (30 or 70 cm, depending on the session). In each block, participants were asked to move the 12 objects in front of them, positioned in 2 different distances based on the tool size (far = 120 cm and near = 80 cm respectively for the 70 cm and 30 cm tool size) while they were sitting steadily next to the table. Specifically, the Far distance was chosen to be near the maximum reachable distance with the full arm stretch plus tool length, ensuring participants used the full extent of their sensorimotor capabilities to extend their peripersonal space. The Near distance required a moderate arm extension. These procedures guaranteed the engagement of the participant's sensorimotor processes for coordinating the tool movement with the goal (grasp and move the objects), and ensured the active limb was stretched in both conditions to promote tool embodiment.

### 2.4. Tactile distance judgment (TDJ) task

TDJ stimuli were administered to the participants' right forearm to investigate changes in the tactile distance perception of the hand using the tool. TDJ task was applied as pre-test and post-test after each

training block (adapted from Jahanian Najafabadi et al., 2023a, 2023b; Jahanian Najafabadi & Godde, 2025). During this task, participants comfortably sat on a chair and placed their right hand on the table to administer TDJ stimuli.

Wooden blocks were prepared with 4 sample pairs of screws, each with different distances between them. The screws had round tips with 9 mm diameter. For TDJ testing parallel to the arm axis ("proximodistal" alignment), 4 sample pairs with distances of 17.8, 39.7, 58.6, and 77.3 mm were administered randomly (cf., Fig. 2). Each trial lasted approximately 1 s. Each sample was presented 5 times, resulting in 20 trials in total.

Immediately after each trial, the participants were asked to report absolute distance estimates, like our previous studies (Jahanian Najafabadi et al., 2023a, 2023b; Jahanian Najafabadi & Godde, 2025). Two steel legs were fixed to a piece of wood, which in turn was attached to the table close to the participant's left hand to use a caliper. The participants were able to adjust the distance between the legs with ease. Using their left hand, participants reported the perceived distance by adjusting the distance between the caliper legs. This would be displayed on the caliper monitor through a mm scale which was recorded by the experimenter accordingly. The stimuli presented to the forearms of the participants was invisible to the participant due to an opaque separator being placed between their eyes and the right forearm throughout the TDJ test. The goal of this measure was to ensure no visual information would be obtained about the real distances, and whether the pairs of stimuli were administered on proximodistal orientation (cf., Fig. 2). We measured how participants judged the distance between pairs of stimuli by looking at the differences (judgment error = estimated distance – actual distance). If the value was positive, it meant they overestimated the distance; if it was negative, they underestimated it. These errors were averaged across five attempts at each distance, and we calculated them separately for the pre-test and post-test. If participants' distance judgments decreased after using the tool, it would suggest that the tool had been integrated into how their brain represents their body, specifically within their existing body schema, or the brain's map of the body.

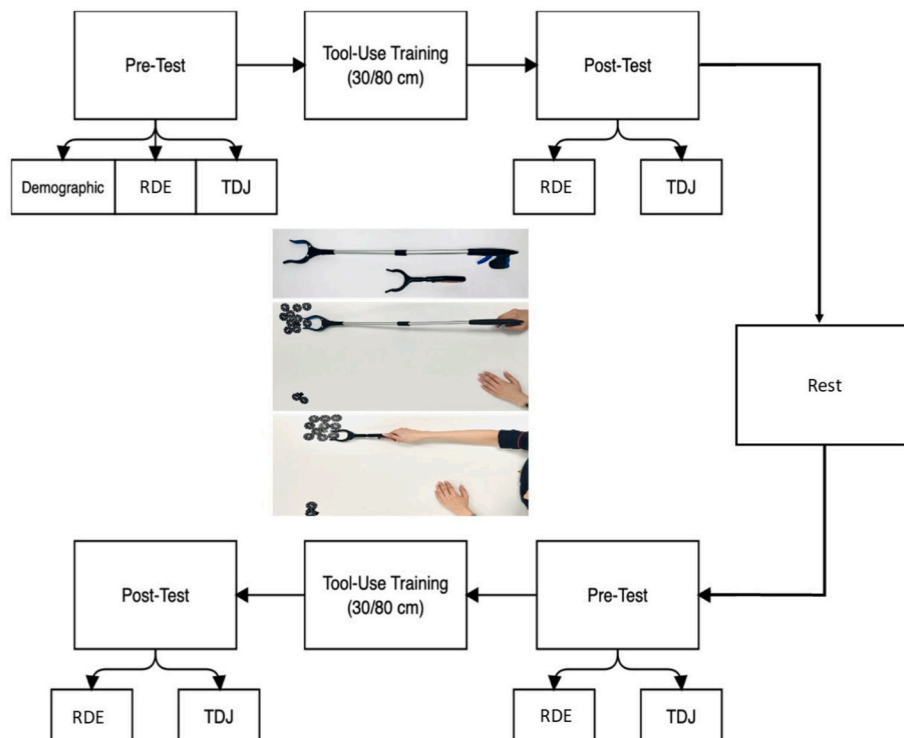


Fig. 1. Schematic of the experimental procedure across two counterbalanced tool-use sessions. Each session included pre- and post-tests (RDE and TDJ), separated by a session of tool-use training with either a short or long mechanical grabber. Tool order was randomized across participants.

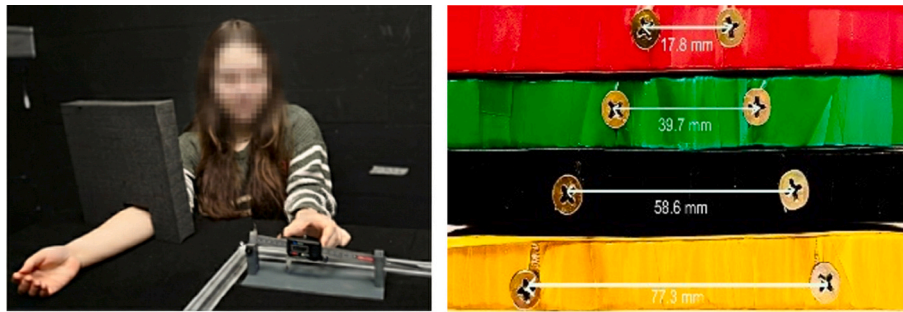


Fig. 2. The tactile distance judgment test was applied to the forearm (proximodistal orientation).

As a result, their arm would be perceived shorter than before, and points along the forearm would seem closer to each other than they did initially.

### 2.5. Reaching distance estimation task (RDE) to assess perceived reaching distance

In our study, peripersonal space is defined via estimated reachability, as peripersonal space is widely understood to encompass the space where actions like reaching occur and is closely tied to sensorimotor function and body representation. The RDE task was adapted from D'Angelo et al. (2018) as a behavioral proxy for peripersonal space to assess changes in the estimated reachability in space (Also see Bourgeois et al., 2014; Witt et al., 2005). A small ball (40 mm in diameter), controlled by the experimenter through a linear actuator, moved towards or away from the participants. The reason for considering the participants' arm length in our measurements is that within the RDE task, participants were specifically asked to perceptually determine what is reachable with the tip of the finger; thus, similar to recent research (Jahanian Najafabadi & Godde, 2025), we reasoned that the reachability estimate is under the effect of the arm's length. Therefore, to neutralize the effect of the arm's length, as a confounding variable, we subtracted the arm's length from the RDE's response, following procedures similar to those used by Bourgeois et al. (2014).

The ball's starting position was 33 cm from the participants' sternum in the withdrawing trials, and at 133 cm in the approaching trials. Participants were asked to estimate the reaching distance, i.e., when they would be able to reach the ball for the last/first time in the withdrawal/approach condition, respectively. These opposing directions allowed us to assess how the initial object position influences reachability judgments (Carello et al., 1989; Rochat & Wraga, 1997). During the task participants were instructed to keep their hands loose behind their bodies. Participants could fine-tune the ball distance by asking the experimenter to move the ball slightly further or forward. Finally, between trials, they were asked to close their eyes. The task was repeated for 6 trials, counterbalancing approaching and withdrawing trials. Participants were precisely instructed as "I will now move this target towards you. Please say stop if you think you could touch it with your arm outstretched". The distance of the ball to the tip of the linear actuator in the final position was measured and recorded for both the approach trials (three trials) and the withdrawal trials (three trials). This score was added to 33 cm and considered as their reported reaching distance. Participants' measured arm length was subtracted from the mean scores of the six trials, resulting in an overall distance estimation error in cm. Positive scores, i.e., overestimation of the reaching distance, indicate a perceived extension of the peripersonal space beyond the own arm, while negative scores suggest perceived underestimation of the peripersonal space and arm reaching distance. Note: participants estimated their reaching space only with the arm without the tool and therefore, changes in RDE errors can be interpreted as indicators of changed perceived arm length. The final RDE error scores were used for

further statistical analysis.

### 3. Data preparation and analysis

Data analysis was performed using R (R Core Team, 2025; v4.1.1; RStudio v1.4.1717) and the Jamovi software environment version 2.5 (The Jamovi project, 2025).

Before the main analyses, assumptions of normality and homogeneity of variance were evaluated for all dependent variables using Levene's test. No substantial violations were detected, supporting the use of General Linear Models (GLMs). To address the research aims, the statistical analysis proceeded in three steps. In Section 3.1.1, a GLM with RDE Error as the dependent variable was used to test the effects of the tool-use training and distance/size variations (Session and Training Space) on spatial representation. In Section 3.1.2, a second GLM with TDJ Error as the dependent variable was conducted to examine the effects of the same manipulation on forearm body schema. In Section 3.1.3, a third GLM was performed with TDJ Error as the dependent variable but with RDE Error added as a covariate in order to evaluate the potential interdependence between the two bodily representations.

Age was modelled primarily as a categorical factor consisting of Adolescents, Young Adults, Mid-age Adults, and Older Adults. This approach was selected because it aligns with distinct developmental stages and captured significant baseline age differences. However, to address the possibility that categorisation might obscure continuous lifespan patterns, additional sensitivity analyses were performed using a continuous quadratic age term (Age\_Centered\_Sq) for both RDE and TDJ. These supplementary results are reported where relevant to confirm the robustness of the null findings.

#### 3.1. Results

##### 3.1.1. Effects of tool-use training on perceived distance estimation depending on training space

GLM was used to analyse whether changes in RDE Error were influenced by tool-use training across near and far training spaces. In this model, changes in RDE Error used as a dependent variable, Session (pre- vs. post-test) and Training Space (near vs. far), and Age Group used as factors, and participants' Arm Length as a covariate. The results revealed no significant main effects of Training Space or Session ( $p > .05$ ), indicating that neither the training context nor the length of the tools had a notable impact on RDE changes. However, the model demonstrated strong explanatory power ( $R^2 = 0.236$ ,  $F(23, 1336) = 17.99$ ,  $p < .001$ ), with Age Group emerging as a significant predictor ( $F(3, 1336) = 31.92$ ,  $p < .001$ ,  $\eta^2 = 0.067$ ). Post-hoc analyses showed that young adults exhibited significantly higher correlation with RDE Error compared to adolescents ( $\beta = 4.56$ ,  $t(1336) = 6.07$ ,  $p < .001$ ) and mid-aged adults ( $\beta = -2.24$ ,  $t(1336) = -2.84$ ,  $p = .005$ ). No significant difference in RDE Error was observed between older adults and adolescents ( $p = .418$ ). Arm Length was also a significant predictor ( $F(1, 1336) = 230.33$ ,  $p < .001$ ,  $\eta^2 = 0.147$ ), confirming its influence on RDE

Error across participants and sessions.

The interactions between Age Group and other factors were mostly non-significant, including the interactions of Age Group  $\times$  Session ( $p = .931$ ;  $\eta^2 = 0.0001$ ), Age Group  $\times$  Training Space ( $p = .542$ ), and the 3-way interaction of Age Group  $\times$  Session  $\times$  Training Space ( $p = .570$ ). However, the interaction effects of Age Group  $\times$  Session with Arm Length controlled as covariate were significant ( $F(6, 1336) = 22.45, p < .001$ ;  $\eta^2 = 0.092$ ). These results reveal that changes in RDE Error

differed depending on Age Group and participants' Arm Length, while Training Space and Session had no notable influence, either individually or through interaction effects ( $p = .42$ ). The post-hoc comparisons confirmed that differences in RDE Error were age-dependent, with young adults consistently different from other groups across Training Space during tool-use training. The findings collectively indicate that age-related factors play a dominant role in RDE Error, while the effects of Training Space are minimal or non-existent ( $\eta^2 = 0.0001$ ). Fig. 3

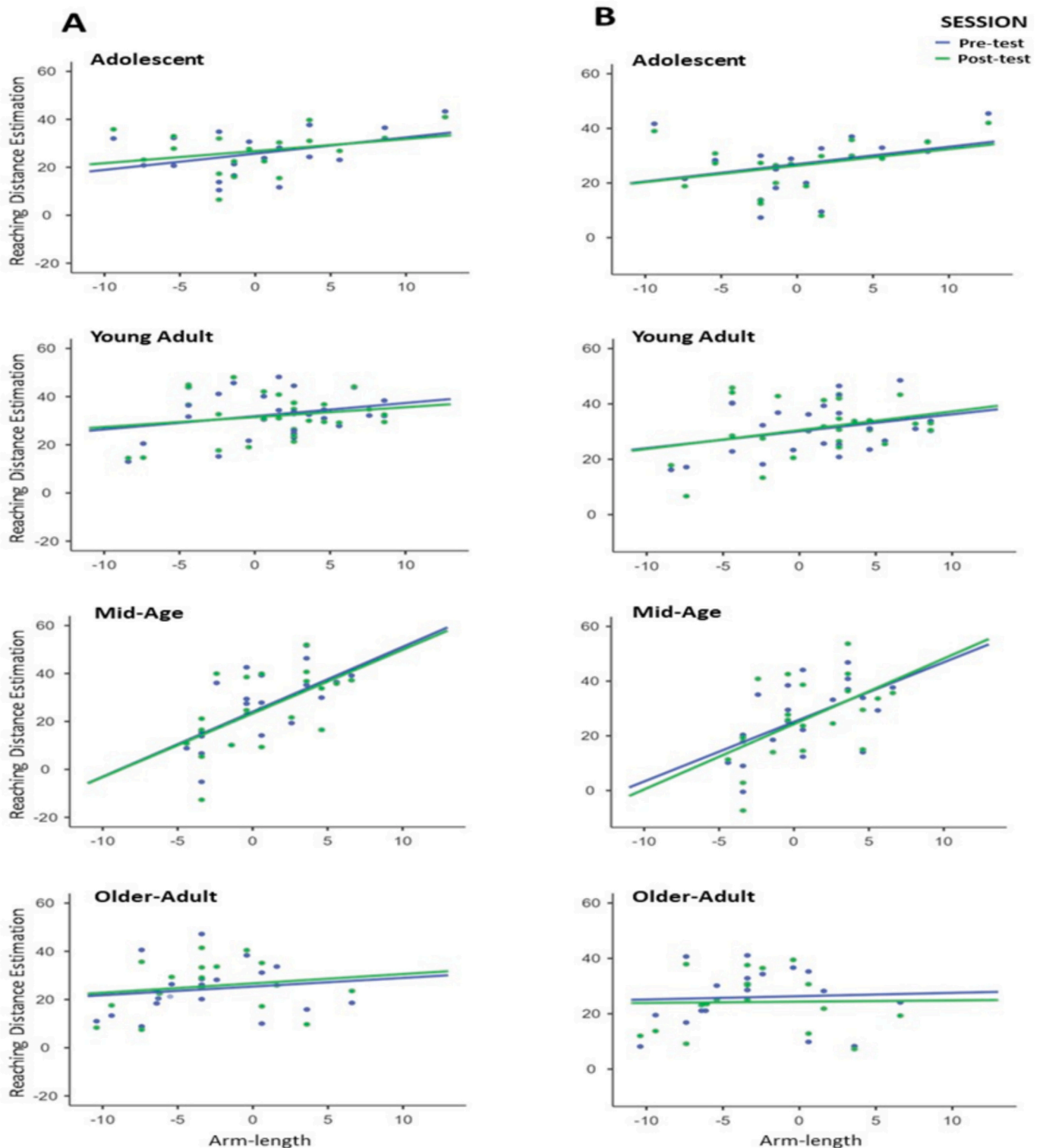


Fig. 3. Reaching distance estimation error (in cm) at baseline and post-test for tool-use training at Near (A) and far Space (B) across all Age Groups.

illustrates the RDE Error at baseline and post-test tool-use training at Near and Far Space across all Age Groups.

3.1.2. Changes in forearm tactile distance judgment during tool-use depending on training space

We first conducted a GLM examining the effect of tool-use training on TDJ Estimation Error as a dependent variable, Age (centered and squared, thus quadratic) as a continuous predictor, along with Session and Training Space (factors), and Distance as a covariate. The overall

model was statistically significant, indicating that Distance contributed substantially to explaining the variance in estimation accuracy ( $F(8, 1340) = 88.3, p < .001, \text{adj.}R^2 = 0.345$ ). The distance between the tactile stimuli was the most robust predictor, showing a strong, significant effect ( $F(1, 1340) = 693.14, p < .001, \eta^2 = 0.341$ ). The negative coefficient ( $\text{beta} = -0.569, p < .001$ ) indicates that as the physical distance between the stimuli increased on the forearm, the reported TDJ Error decreased. The quadratic term for age ( $\text{Age\_Centered\_Sq}$ ) showed a small but significant main effect ( $F(1, 1340) = 7.21, p = .007, \eta^2 =$

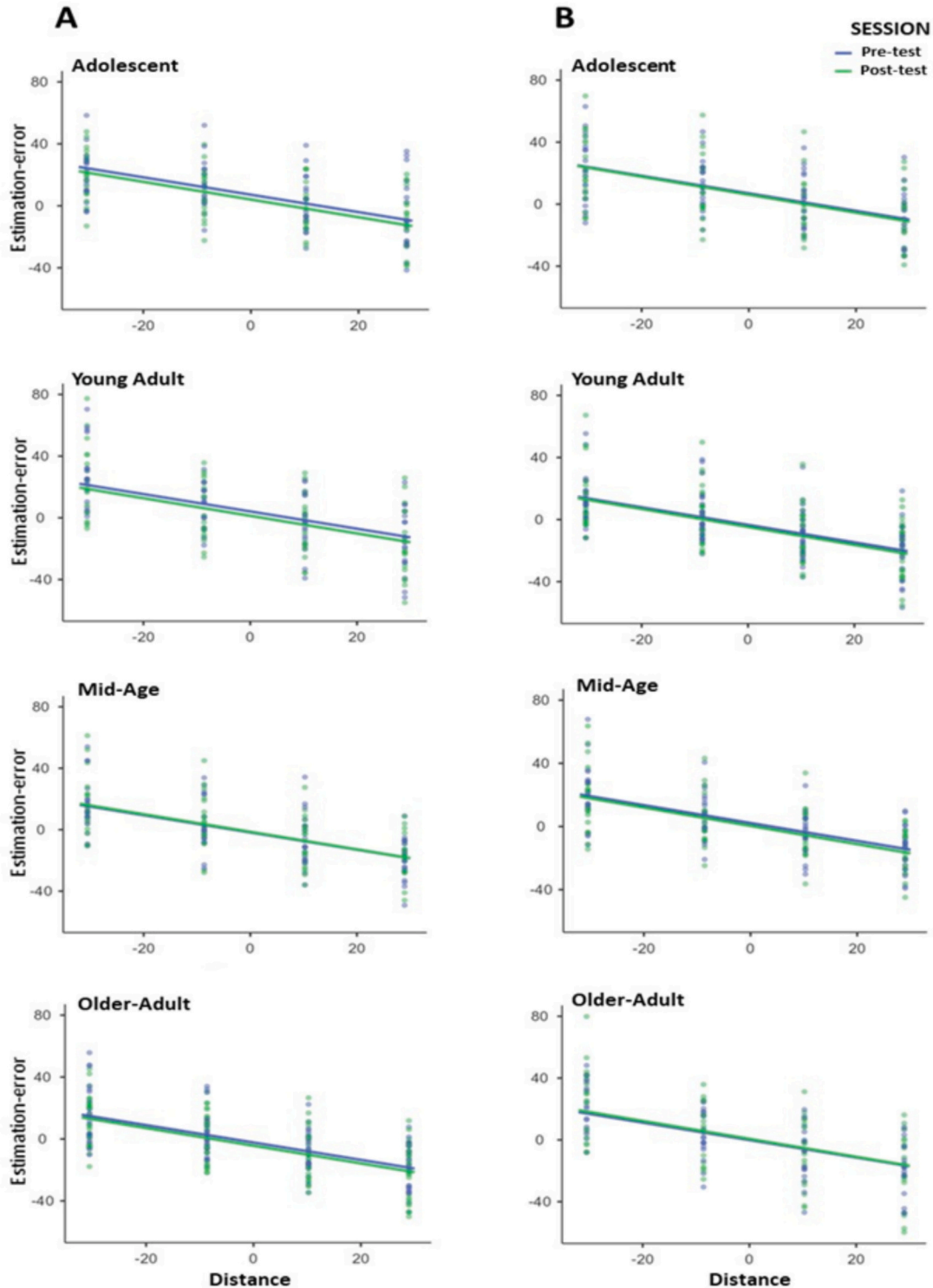


Fig. 4. Changes in RDE error based on training space at Near(A) and Far Space (B) for Age Groups.

0.005). The positive coefficient ( $\beta = 0.003, p = .007$ ) suggests a non-linear, U-shaped relationship between age and TDJ Estimation Error, where accuracy is highest in young adulthood and drops off in both adolescence and older adulthood. Neither Session ( $F(1, 1340) = 2.098, p = .148$ ) nor Training Space ( $F(1, 1340) = 0.013, p = .908$ ) had a significant main effect on TDJ Estimation Error.

To investigate the factors influencing the forearm tactile distance perception, GLM was applied with TDJ Error as a dependent variable. The model included Session (pre-test vs. post-test), TDJ stimuli Distance,

Training Space (near vs. far), and Age Group as a categorical factor. Interactions among these factors, such as Session  $\times$  Distance; Session  $\times$  Training Space, and Session  $\times$  Age Group, were also included. The overall model was significant ( $F(17, 1331) = 46.02, p < .001, \text{adj. } R^2 = 0.362$ ), indicating that the predictors substantially contributed to explaining changes in estimation accuracy.

Results revealed TDJ stimuli Distance as a robust predictor ( $F(1,1331) = 715.72, p < .001, \eta^2 = 0.339$ ), showing that TDJ Error was significantly lower for smaller stimuli distances compared to larger

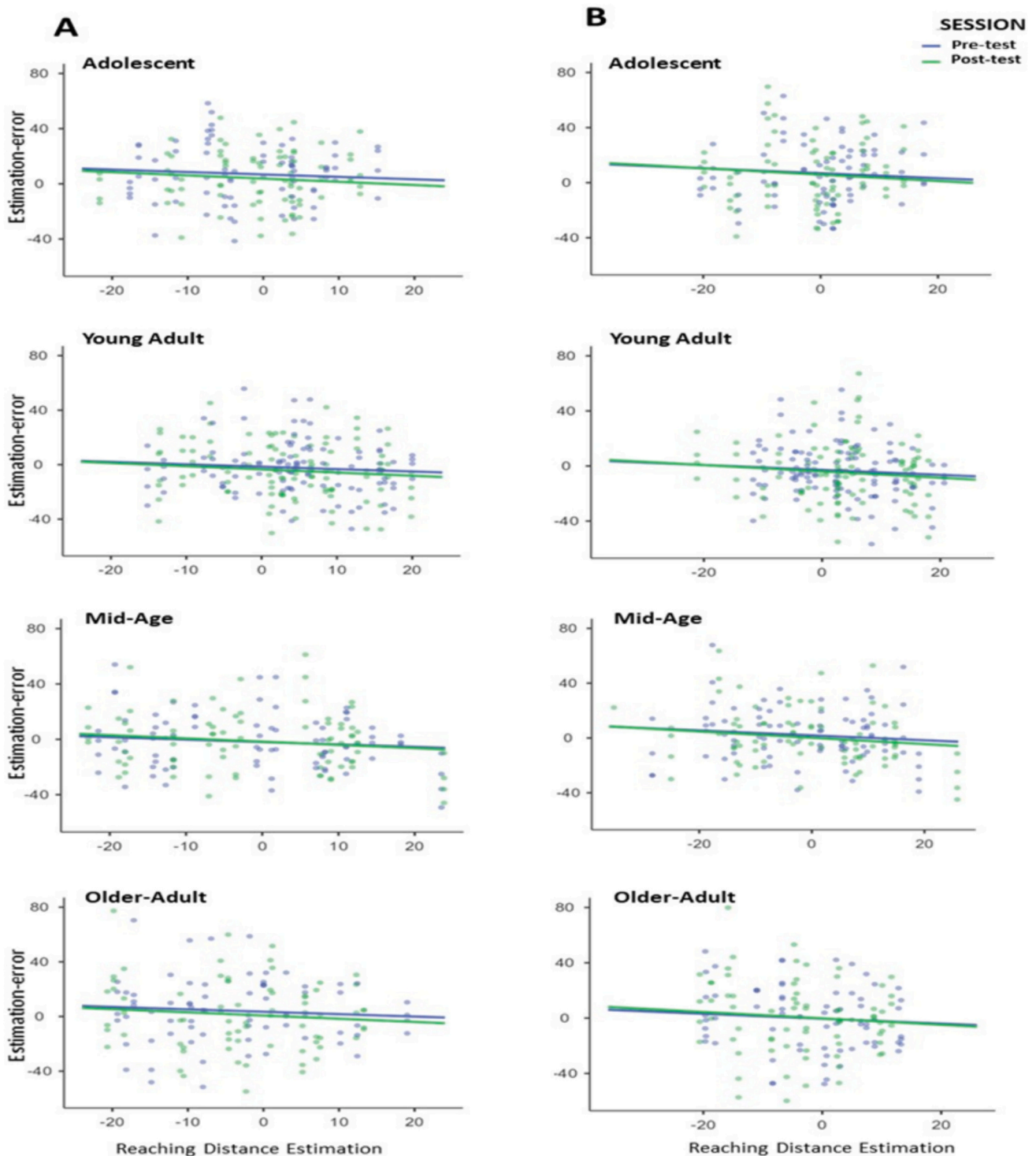


Fig. 5. Tactile Distance Estimation Error (in mm) and Reaching Distance Estimation (in cm) at baseline and post tool-use training at Near (A) and (B) Far Space for all age groups.

stimuli distances ( $\beta = -0.57$ ,  $t(1331) = -26.75$ ,  $p < .001$ ). Age Group also had a significant effect ( $F(3,1331) = 19.52$ ,  $p < .001$ ,  $\eta^2 = 0.028$ ). Post-hoc comparisons revealed that young adults demonstrated significantly lower errors compared to adolescents ( $\beta = -9.77$ ,  $t(1331) = -7.56$ ,  $p < .001$ ), mid-age adults ( $\beta = -6.23$ ,  $t(1331) = -4.52$ ,  $p < .001$ ), and older adults ( $\beta = -4.57$ ,  $t(1331) = -3.22$ ,  $p = .001$ ). However, neither Session ( $F(1, 1331) = 2.01$ ,  $p = .156$ ,  $\eta^2 = 0.001$ ) nor Training Space ( $F(1, 1331) = 0.02$ ,  $p = .902$ ,  $\eta^2 < 0.001$ ) showed significant effects on tactile distance perception. Similarly, no significant interactions were found between Session and Distance ( $F(1, 1331) = 0.09$ ,  $p = .77$ ,  $\eta^2 < 0.001$ ), Session and Training Space ( $F(1, 1331) = 0.33$ ,  $p = .565$ ,  $\eta^2 < 0.001$ ), or Session and Age Group ( $F(3, 1331) = 0.09$ ,  $p = .963$ ,  $\eta^2 < 0.001$ ). Interaction effects of Training Space  $\times$  Age Group ( $F(3, 1331) = 1.37$ ,  $p = .250$ ,  $\eta^2 = 0.002$ ) and Session  $\times$  Training Space  $\times$  Age Group ( $F(3, 1331) = 0.39$ ,  $p = .758$ ,  $\eta^2 = 0.001$ ), were also not significant suggesting that that while Distance and Age Group significantly influenced estimation accuracy, factors such as Training Space and the interaction effects did not contribute meaningfully to the observed variance. Fig. 4 illustrates forearm Tactile Distance Estimation Error per Distance compared Session (Pre- vs Post-test) and Training Space (Near vs Far).

### 3.1.3. Age-dependent effect of tool-use training on forearm tactile distance perception and perceived reaching distance

In the next step, we further investigated whether tool-use training at Near or Far Training Space in various age groups and RDE Error as covariate affects the TDJ Error. In this model, TDJ Estimation Error was used as a dependent variable, Session, Age Group and Training Space as Factors and RDE Error and Distance as covariates. Results indicated the model explanatory power at (adj.  $R^2 = 0.373$ ). From the ANOVA analysis, the model showed significant effects for Distance, RDE Error, and Age Group, but not for Training Space or the interactions involving these factors. Specifically, TDJ stimuli Distance had a significant effect on TDJ Error ( $p < .001$ ), with a large effect size ( $\eta^2 = 0.338$ ), indicating that larger distances were associated with greater TDJ Errors indicating overestimation across trials. RDE Error also significantly affected TDJ Estimation Error ( $p < .001$ ), although with a smaller effect size ( $\eta^2 = 0.010$ ). Age Group showed a significant effect, with older adults and mid-age adults exhibiting larger TDJ Estimation Error compared to adolescents ( $p < .001$ ,  $\eta^2 = 0.046$ ). No significant effects were observed for Training Space, nor were any significant interactions found between Session, Training Space, and Age Group. Fig. 5 illustrate Tactile Distance Estimation Error and Reaching Distance Estimation at baseline and post tool-use training at Training Space for all age groups.

Results further revealed the effect of TDJ stimuli Distance was negative, indicating that as the stimuli Distance administered on the forearm, TDJ Error decreased ( $\beta = -0.581$ ,  $p < .001$ ). There were no significant differences between Near and Far Training Spaces in terms of Estimation Error ( $p = .953$ ). Age Group comparisons revealed that both young adults and mid-age adults had significantly smaller tactile distance Estimation Error compared to adolescents. No significant interactions were observed between Session and the other factors (TDJ Stimuli Distance, RDE Error, Training Space, Age Group), suggesting that the changes in Estimation Error across sessions were not dependent on these factors. Post-hoc comparisons did not reveal any significant differences between training conditions (near vs. far) at different sessions, reinforcing the absence of a significant effect of Training Space. Fig. 4 illustrates TDJ Error and RDE Error at baseline and post tool-use training at Near and Far Space for all age groups.

## 4. Discussion

In the present study, we aimed to expand upon previous findings regarding the forearm representational plasticity observed in adolescents during puberty (Martel et al., 2016) and young adults (Jahanian Najafabadi et al., 2023a; Martel et al., 2017; Miller et al., 2014). These

studies suggested that the integration of physical or virtual tools into the existing body schema occurs when individuals engage in tool-use. However, findings are not consistent across age groups. While some studies have reported preserved body schema plasticity in older adults (e.g., Sposito et al., 2012), others show a marked decline with age (e.g., Jahanian Najafabadi et al., 2023b). This inconsistency raises questions about how and to what extent aging influences body schema adaptability. To address these questions, our previous research (Jahanian Najafabadi et al., 2023b) found no evidence of forearm body schema plasticity in older adults when using the same training paradigm that induced changes in younger participants (Jahanian Najafabadi et al., 2023a). Notably, neither learning efficiency nor tool-use performance declined with age, suggesting a relatively stable body schema in late adulthood.

In the current study, participants across various age groups participated in two experimental sessions designed using a well-established tool-use paradigm (Cardinali et al., 2012; Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009; Miller et al., 2014, 2017). These sessions required grasping objects located at near or far distances using a short or long mechanical grabber. The main objective was to examine body representational plasticity across sessions and determine whether the observed effects were consistent with prior research. We also investigated whether tool-use training in near and far spaces (using different tool sizes) modulated arm representation, particularly regarding perceived reaching distance within and beyond arm's length. By maintaining a consistent experimental design, we aimed to compare outcomes across age groups to better understand how perceived forearm tactile distance and reaching estimates vary before and after tool-use training under both experimental conditions.

### 4.1. Tool-use training does not induce significant changes in forearm distance perception across age groups

Our study results showed that tool-use training, whether in near or far training spaces, did not lead to significant changes in forearm tactile distance perception across all age groups. At baseline, all age groups exhibited smaller tactile distance estimation errors compared to adolescents. The largest difference was observed between adolescents and young adults, with notable differences also found between middle-aged and older adults. These findings highlight the developmental changes that occur during puberty and continue into later adulthood which results in a decline in body representational plasticity (Jahanian Najafabadi et al., 2023a, 2023b; Martel et al., 2019).

The lack of tool incorporation during the far space training block in older adults could be attributed to the increased cognitive and attentional demands required to extend the perceived reach of the tool, which may exceed the capabilities of this age group (Costello & Bloesch, 2017). Moreover, the age-related declines in sensorimotor integration and decreased flexibility in updating body representation (Sorrentino et al., 2020) can be the main explanation of non-malleable body schema in our results.

Another possible explanation for the lack of significant effects of the training sessions on forearm tactile distance perception updates could be the complexity and cognitive demands associated with the tool-use task. Previous research has shown that the ability to incorporate tools into mental body representation can be influenced by factors such as task difficulty, familiarity with the tool, and the extent of training involved (Baccarini et al., 2014; Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009; Witt et al., 2005). In this study, the specific tool-use task, which involved grasping objects in both near and far spaces, may not have been sufficiently challenging or novel for the older adult participants. This could have limited the degree of body representational plasticity observed, as older individuals may have already developed efficient strategies for interacting with objects in their environment, reducing the need for further adaptation. Consequently, the lack of significant changes in the forearm tactile distance perception could be a

result of the task's cognitive demands not being sufficient to elicit the necessary level of sensorimotor adaptation, particularly in older adults who may have had more experience with similar tasks (Jahanian-Najafabadi et al., 2025).

As an alternative theory, to gain a deeper understanding of embodiment, we can explore the cognitive framework known as "Radical Embodiment" (For review: Schettler et al., 2019). According to this perspective, the incorporation of a tool into an existing representation and any resulting changes are not necessarily prerequisites for embodiment. Instead, embodiment is viewed as a dynamic coupling between various components of the cognitive system, such as the body and the tool. This approach emphasizes that the cognitive system functions as a complex, self-organized entity, where embodiment emerges not from a static reconfiguration of representation, but from the interactive, adaptive relationship between the body and its tools within the context of the environment (Dotov et al., 2010; Van Orden et al., 2005).

A specific interpretation of this dynamic is provided by the cascade dynamics or multifractal perspective (Mangalam et al., 2022). This framework posits that the relationship between the organism and the environment exists along porous and blurry boundaries (Gibson, 1979 reported by Gibson, 2014). Tool-use, in this context, is simply another intermittent function resting on cascades—nonlinear interactions that blend information across nested scales of activity, from neural firing to gross movement. The continuous flow of fluctuations (measured as multifractal structure) spans the organism, the tool, and the environment (Mangalam & Kelty-Stephen, 2020). This means the tool is an intermittent participant that blinks in and out of existence as a separate entity from the body. From this highly dynamic view, the persistence of the bodily and spatial representations, rather than being a null finding, may reflect this fluid, scale-free flexibility inherent in the self-organized system, which constantly adapts without requiring a static remapping of the body schema.

The broader literature on tool-use is framed by a debate between various embodied and disembodied views, which interpret the significance of our null findings differently. For instance, the Ecological-Dynamics approach (for review; Mangalam et al., 2022; Pagano & Day, 2020) views tool-use as fundamentally embodied, occurring when an environmental object temporarily alters the body's capability for action. In this framework, successful tool-use requires the spontaneous and temporary assembly of task-specific detection units and the integration of the tool into the emergent movement synergies of the body-plus-tool system (Tuitert et al., 2020). The lack of observed plasticity in our study, from this perspective, might imply that the tools or training were insufficient to necessitate the emergence of a new tooling synergy or the detection of novel affordances (Pagano & Day, 2020).

Conversely, the Technical-Reasoning Hypothesis (e.g., Osiurak et al., 2020) emphasizes a disembodied, cognitive foundation. This view posits that uniquely human tool proficiency stems from causal and analogical reasoning about physical principles, with sensorimotor control merely realizing the plan generated by this higher-level reasoning. Under this perspective, highly practiced or non-challenging tasks (as we proposed for our older adults) may rely heavily on pre-existing technical knowledge and motor schemas (Osiurak et al., 2020), thereby bypassing the need for acute sensorimotor remapping in body representations.

Considering these theoretical frameworks, we propose that, despite the lack of significant effects of tool-use on bodily and spatial representations such as body schema and peripersonal space, tool embodiment, as a result of the training sessions, cannot be dismissed. Notably, the mainstream frameworks discussed in our study emphasize that tool embodiment involves more than just spatial integration, but it also includes subjective and functional aspects such as the sense of agency and ownership (Schettler et al., 2019). Many tool-use studies have primarily focused on spatial embodiment or agency, often underestimating the role of sense of ownership which has been directly addressed in recent research (Jahanian Najafabadi et al., 2023a). This may be due to

assumptions that tools, unlike body parts or passive objects, are less likely to elicit ownership. However, evidence from the rubber hand illusion (Botvinick, 2004; Botvinick & Cohen's, 1998) showed that non-biological objects can evoke ownership under the right conditions, suggesting that ownership in tool contexts has not been similarly explored.

#### 4.2. Tool-use training did not induce changes in the distance estimation task across all age groups

Overall, the lack of significant changes in perceived reaching distance were demonstrated by the absence of any notable training effects across the training blocks and age groups. In other words, using tools in different training settings did not lead to observable expansions of near space into far space or vice versa. The enlargement in the perceived reaching distance can be triggered and be dependent on many elements due to the multimodal nature of this representation (i.e., peripersonal space) which can be affected by visual, auditory, and tactile stimuli (Avenanti et al., 2012; Serino et al., 2009). Moreover, bodily criteria such as body size can be a factor in the size of the peripersonal space, which was the reason that we took participants' arm's length into account in our measurements (Longo & Lourenco, 2007), and put this measure as a covariate in our model for spatial representation. As predicted, the arm's length had a significant effect on the perceived reaching distance updates which indicate the intertwined relation between the body image, as a conscious subjective perception of body size, and spatial representation.

Differences in measurement techniques and ongoing theoretical debates regarding the definition of peripersonal space have led to varying criteria for identifying peripersonal space enlargement. In Iriki et al. (1996), a study on monkeys demonstrated that tool-use induced peripersonal space, as the brain adapted to represent the tool as an extension of the arm, thereby incorporating it into the body's immediate action space. In contrast, Witt et al. (2005) described peripersonal space modifications as a remapping process, where more distant objects are perceived as closer and integrated into our action space. Additionally, previous studies (Farnè et al., 2005; Farnè & Ládavas, 2000) have emphasized that specific conditions are required for inducing peripersonal space updates, such as engaging with a tool in an active, goal-directed, and effective manner.

The lack of significant changes in perceived distance estimation in the adolescent group may suggest that sensorimotor associations are still being actively constructed, as also evidenced by the differences in tool-use kinematics observed between blocks in the adolescent group of prior research (Martel et al., 2021). This ongoing process might be influenced by the more frequent use of the tool within each training block. The nearly identical RDE performance in both mid-age and older adults reflects the stability of body-size representation (i.e., body image), indicating that long-term, conscious sensorimotor representations of the body remain consistent across these two age groups (Melzack, 1997; O'Shaughnessy, 1995). A similar consistency was reported by De Vignemont et al. (2005), who proposed that the absence of tactile perception updates (measured by TDJ) in response to bodily illusions, such as the illusion of body part shrinkage, can be attributed to the weighted combination of online body schema and persistent body image. The stability and consistency of body representations are further supported by findings from other studies, while Martel et al. (2021), reported an inconsistent kinematic pattern when comparing the first and last tool-use sessions in adults. This stable movement pattern can be interpreted as a reduced rate of motor learning in adults, a phenomenon previously reported in studies showing the absence of practice effects in adults (Cardinali et al., 2011; Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009), although findings are contradictory (Jahanian Najafabadi et al., 2023b). With regard to the lack of significant changes in perceived distance estimation observed in our results, one potential explanation lies in the limitations of our experimental

paradigm, particularly the nature and duration of the training protocol. Previous studies have demonstrated that more intensive and prolonged tool-use training leads to modifications in peripersonal space boundaries (Farnè & Ládavas, 2000). The training protocol used in this study may not have been sufficiently intensive or long-lasting to induce measurable changes in peripersonal space representation by such measurements e. g., RDE task.

#### 4.3. Perceived reaching distance as a predictor of body schema modulation

Although our results differ from some of previous studies that have shown tool-use training expanding the boundaries of peripersonal space (Ládavas & Serino, 2008) or updating the body schema (e.g., Cardinali, Brozzoli, & Farnè, 2009; Cardinali, Frassinetti, et al., 2009), the explanation for these discrepancies may lie in the complex relationship between peripersonal space and body schema. Different theoretical models, such as the “dyadic model” (body schema vs. body image) (Cardinali et al., 2011; Head & Holmes, 1911) and the triadic model for body representation (body schema vs. body image vs. body structure description), have contributed to the ambiguity in defining the boundaries between various forms of bodily spatial representation (Sirigu et al., 1991; Buxbaum and Coslett, 2001; Schwoebel & Coslett, 2005). As highlighted in the study by Cardinali, Brozzoli, and Farnè (2009) and Cardinali, Frassinetti, et al. (2009), the shared properties of body schema and peripersonal space, including their plasticity and involvement in motor coordination, make these two concepts nearly inseparable. However, some authors have suggested that dissociating the two could be achieved through experimental designs that emphasize the necessity of the tool's physical continuity for inducing body schema changes without affecting peripersonal space representations.

#### 4.4. Limitation and suggestion

While our study provides important insights into the relationship between tool-use and body representational plasticity across the lifespan, there are several limitations that should be considered and addressed by potential improvement in future research.

##### 4.4.1. Tool characteristics and adaptation

One limitation of our study is the use of a tool that, while not specifically designed for this experiment but has been used extensively in prior tool-use research, could be somewhat familiar to participants due to its resemblance to everyday objects. This familiarity could reduce the need to create new sensory associations during the tool-use task. Consequently, the participants may have relied on pre-existing sensorimotor knowledge, which might have lessened the plasticity effects expected to be observed in body representations' updates. From the Ecological-Dynamics perspective, this reliance on existing knowledge suggests the tool may have already achieved functional transparency (for review; Mangalam et al., 2022), where its affordances have been fully detected and exploited, limiting the degree of novel sensorimotor adaptation. Future research should explore the use of more novel, and in comparison, unfamiliar tools that would likely require participants to form new sensorimotor associations, thus potentially inducing more pronounced changes in body representation and enhancing our understanding of the relationship between tool-use and sensorimotor representational plasticity.

Another limitation pertains to the size of the tools used in our study. Specifically, the smaller tool might not provide sufficient length to induce somatosensory remapping or significantly alter spatial perception. According to research on tool-use and space remapping (Iriki et al., 1996), larger tools are more effective in extending spatial representation by incorporating far space into near space. Although the study by Iriki and colleagues was conducted in monkeys, in this study focused on human subjects, the small tool may not have been large enough to

trigger such remapping in distance estimation. From an ecological-dynamics perspective, a too-small tool may not sufficiently alter the geometry of the action system or the dynamic constraints enough to force the emergence of a distinct tooling synergy (Tuitert et al., 2020), thereby failing to trigger the necessary update of effectivities. To address this limitation in future studies, we recommend using a greater range of tool sizes, including longer tools, which could offer more opportunities for spatial remapping and body schema updates, and thus provide a clearer picture of how manipulation of tool size affects body representation.

##### 4.4.2. Methodological constraints and analysis

The TDJ paradigm is widely used to assess body representation updates but remains methodologically limited. For instance, the skin of the hand and forearm contains mechanoreceptors that vary in density across regions. Areas with greater receptor density, such as the fingertips, receive disproportionately larger cortical representation, a phenomenon known as cortical magnification. This uneven somatosensory mapping generates distortions in body representation that can change with age (García-Piqueras et al., 2019; Kuroki, 2021). Such distortions may lead to perceptual errors, including overestimation of tactile distances or misjudgment of body-part proportions. These errors stem from the anisotropic neural representation of the body surface (Longo, 2020), whereby distances oriented proximodistally may be perceived as smaller than mediolateral distances (Longo, 2020; Longo & Haggard, 2011). TDJ is often employed as an indirect marker of body schema plasticity, based on the assumption that perceived tactile distances reflect internal models of body size, shape, and structure (Miller et al., 2014). However, its validity as a consistent indicator of schema updating—particularly in tool-use contexts—remains debated. A recent study using a more complex gather-and-sort task did not observe changes in TDJ or forearm bisection judgments (for review; Bell & Macuga, 2022), suggesting that either the task did not induce tool-related adaptation or that TDJ may not capture all dimensions of body schema plasticity. Related perceptual distortions have been reported by Peviani et al. (2019), who showed that misjudgments of limb proportions likely arise from distinct mechanisms for perceiving limb length versus width. Moreover, these distortions are influenced not only by somatosensory representations but also by non-somatic factors such as vision (For review, Serino & Haggard, 2010).

While the use of TDJ is one of the most established tools for investigating body schema changes (Longo & Haggard, 2011; Miller et al., 2014, 2017; Sun & Tang, 2019), its interpretation is challenging because TDJ may reflect both body image and body schema—the two sub-components of body representation—which are dynamic and interdependent constructs. Distinguishing their separate contributions to task performance is therefore difficult. Future research would benefit from refining the TDJ paradigm, perhaps by integrating it with complementary measures of sensorimotor integration and neural measurement (e. g., EEG), to better capture how tool-use modulates both body ownership and body representation.

##### 4.4.3. Statistical power and interpretation of null results

Bayesian Model Comparison was performed using JASP (Version 0.18.3) by implementing a Bayesian ANOVA. We used default Jeffreys-Zellner-Siow (JZS) priors (Cauchy distribution, scale  $\gamma = 0.707$ ) and compared all possible models (including main effects and interactions) against the null model. Evidence was quantified using the posterior model probability ( $P(M|data)$ ) and the Bayes Factor ( $BF_{10}$ ), which represents the likelihood of the alternative model relative to the null. In cases where the null model was the best-fitting model, we report  $BF_{01}$  (the inverse of  $BF_{10}$ ) to quantify evidence in favor of the null.

The power of our study to address the full scope of tool-use plasticity is subject to additional constraints. Specifically, the sample size within each of the four distinct age cohorts may have limited the statistical power necessary to detect all effects. Furthermore, the duration and repetition of the acute tool-use training blocks may have been

inadequate to induce enduring changes in the body schema, particularly in age groups exhibiting reduced neuroplasticity (e.g., older adults). However, to move beyond simply stating the “absence of evidence” inherent in null frequentist findings, we conducted a Bayesian Model Comparison on the TDJ task outcome. This analysis provided substantial evidence in favor of the null model and revealed that the null model was the most probable model given the data ( $P(M|data) = 0.51$ ), outperforming the prior odds by a factor of 7.19 ( $BF_M = 7.19$ ). Critically, the Bayes Factors ( $BF_{10}$ ) for models incorporating our experimental factors were very small, indicating substantial evidence for the null hypothesis: specifically, the data were 8.49 times more likely under the null than the session model ( $BF_{10} = 0.12$ ) and 16.29 times more likely under the null than the training space model ( $BF_{10} = 0.06$ ). All models including the experimental factors of Session and Training Space were decisively rejected, suggesting the null result is not merely a consequence of low statistical power, but constitutes quantifiable evidence for the absence of an acute tool-use induced change in forearm tactile distance perception under these specific training parameters.

Similarly, the RDE task was subjected to Bayesian Model Comparison. In this task, the analysis provided extremely strong evidence for a model incorporating age (squared) ( $P(M|data) = 0.84$ ,  $BF_{10} = 1092.4$  for the Age-Squared model vs. the null), with this model being approximately 35.6 times more likely than at the start of the analysis ( $BF_M = 35.6$ ). Conversely, the models containing only the training factors were strongly rejected ( $BF_{10} = 0.06$  for both session and training space), confirming that while the null hypothesis regarding training effects is supported, age is the critical driver of variability in perceived reaching distance. This confirms that while the null hypothesis regarding the training effects is strongly supported (evidence of absence), Age is the critical factor driving variability in perceived reaching distance, thereby confirming the stability of spatial representation across sessions but highlighting the major influence of lifespan developmental changes. Therefore, our null findings regarding changes in body schema should be interpreted as the absence of acute, large-magnitude effects under these specific training parameters. Interestingly, recent research showed that age was the strongest predictor of tool-use performance, with younger adults consistently completing the task more quickly than older adults (Jahanian-Najafabadi et al., 2025). Given evidence that motor learning and body representation improve with repeated exposure and practice (D'Angelo et al., 2018), future work should consider longer training periods, more immersive paradigms (Sykes, 2023) and consider the measurement of each trial duration and kinematics to meet the conditions required for robust metric adaptation. This approach could allow for a more detailed examination of the temporal dynamics of body schema plasticity and the role of repetition in enhancing sensorimotor integration during tool-use.

A potential source of bias in this study may arise from the sampling characteristics of the different age groups. Specifically, the average age within the adolescent group was approximately 17 years, while the young adult's group had an average age of 21 years. This age gap is relatively small, and the developmental and neuroplastic differences between these groups may not be as pronounced as we initially anticipated similar to the prior research (Martel et al., 2021). Consequently, this similarity in age ranges could have obscured potential differences in body representational plasticity between the groups. Future studies should aim for larger age differences between groups to better capture the effects of age-related changes in sensorimotor processing and body representation. Additionally, using more diverse and balanced age cohorts could help mitigate any potential sampling biases and offer clearer insights into the relationship between aging and body schema plasticity.

## 5. Conclusion

In summary, our study found no evidence that tool-use significantly alter the forearm tactile distance perception or perceived distance estimation across different age groups. While participants perceiving

reduced tactile distances on the forearm, their overall body representation remained largely unchanged by the tool-use training, suggesting that short-term tool-use alone maybe is insufficient to modify these deeply ingrained sensorimotor processes. Similarly, perceived distance estimation did not show a significant expansion with tool-use, indicating that longer or more immersive experiences may be required to induce such effects. These findings suggest that while our ability to use tools improves with age, the brain's integration of tools into our sense of body and space remains relatively stable. Future research should explore how factors such as extended training, different tool types/sizes, and task demands influence this relationship over time.

## Ethic statement

The experimental procedure was approved by the Ethics Committee of the Bielefeld University (EUB-2023-120-S).

## CRedit authorship contribution statement

**Amir Jahanian Najafabadi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alireza Rastegari:** Writing – original draft, Data curation. **Hadis Imani:** Writing – review & editing, Validation, Data curation. **Matthew R. Longo:** Writing – review & editing, Validation.

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## Declaration of competing interest

Authors declare no conflict of interest.

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## Data availability

Datasets used to generate these results are made available in OSF under the project A Lifespan Study on Body Schema and Perceived Reaching Distance. Datasets can also be requested from corresponding author by email.

## References

- Assaiante, C., Barlaam, F., Cignetti, F., & Vaugoyeau, M. (2014). Body schema building during childhood and adolescence: A neurosensory approach. *Neurophysiologie Clinique*, 44(1), 3–12. <https://doi.org/10.1016/j.neucli.2014.10.125>
- Avenanti, A., Anella, L., & Serino, A. (2012). Suppression of premotor cortex disrupts motor coding of peripersonal space. *NeuroImage*, 63(1), 281–288. <https://doi.org/10.1016/j.neuroimage.2012.06.063>
- Baber, C. (Jan 2006). Cognitive aspects of tool use. *Applied Ergonomics*, 37(1), 3–15. <https://doi.org/10.1016/j.apergo.2005.06.004>
- Baccarini, M., Martel, M., Cardinali, L., Sillan, O., FarnÀ, A., & Roy, A. C. (2014). Tool use imagery triggers tool incorporation in the body schema. *Frontiers in Psychology*, 5. <https://doi.org/10.3389/fpsyg.2014.00492>
- Bahmad, S., Miller, L. E., Pham, M. T., Moreau, R., Salemme, R., Koun, E., ... Roy, A. C. (2020). Online proprioception feeds plasticity of arm representation following tool-use in healthy aging. *Scientific Reports*, 10(1). <https://doi.org/10.1038/s41598-020-74455-5>
- Bassolino, M., Franza, M., Guanziroli, E., Sorrentino, G., Canzoneri, E., Colombo, M., ... Serino, A. (2022). Body and peripersonal space representations in chronic stroke patients with upper limb motor deficits. *Brain Communications*, 4(4), Article fca179. <https://doi.org/10.1093/braincomms/fcac179>

- Bell, J. D., & Macuga, K. L. (2022). Are tools truly incorporated as an extension of the body representation?: Assessing the evidence for tool embodiment. *Psychonomic Bulletin & Review*, 29, 343–368. <https://doi.org/10.3758/s13423-021-02032-6>
- Botvinick, M. (2004). Probing the neural basis of body ownership. *Science*, 305(5685), 782–783. <https://doi.org/10.1126/science.1101836>
- Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature*, 391(6669), 756. <https://doi.org/10.1038/35784>
- Bourgeois, J., Farné, A., & Coello, Y. (2014). Costs and benefits of tool-use on the perception of reachable space. *Acta Psychologica*, 148, 91–95. <https://doi.org/10.1016/j.actpsy.2014.01.008>
- Buxbaum, L. J., & Coslett, H. B. (2001). Specialised structural descriptions for human body parts: Evidence from autotopagnosia. *Cognitive Neuropsychology*, 18(4), 289–306. <https://doi.org/10.1080/02643290126172>
- Canzoneri, E., Ubaldi, S., Rastelli, V., Finisguerra, A., Bassolino, M., & Serino, A. (2013). Tool-use reshapes the boundaries of body and peripersonal space representations. *Experimental Brain Research*, 228(1), 25–42. <https://doi.org/10.1007/s00221-013-3532-2>
- Cardinali, L., Brozzoli, C., & Farné, A. (2009). Peripersonal space and body schema: Two labels for the same concept? *Brain Topography*, 21(3–4), 252–260. <https://doi.org/10.1007/s10548-009-0092-7>
- Cardinali, L., Brozzoli, C., Finos, L., Roy, A., & Farné, A. (2016). The rules of tool incorporation: Tool morpho-functional & sensori-motor constraints. *Cognition*, 149, 1–5. <https://doi.org/10.1016/j.cognition.2016.01.001>
- Cardinali, L., Brozzoli, C., Urquizar, C., Salemme, R., Roy, A., & Farné, A. (2011). When action is not enough: Tool-use reveals tactile-dependent access to body schema. *Neuropsychologia*, 49(13), 3750–3757. <https://doi.org/10.1016/j.neuropsychologia.2011.09.033>
- Cardinali, L., Frassinetti, F., Brozzoli, C., Urquizar, C., Roy, A. C., & Farné, A. (2009). Tool-use induces morphological updating of the body schema. *Current Biology*, 19(13), 1157. <https://doi.org/10.1016/j.cub.2009.06.048>
- Cardinali, L., Jacobs, S., Brozzoli, C., Frassinetti, F., Roy, A. C., & Farné, A. (2012). Grab an object with a tool and change your body: Tool-use-dependent changes of body representation for action. *Experimental Brain Research*, 218(2), 259–271. <https://doi.org/10.1007/s00221-012-3028-5>
- Cardinali, L., Zanini, A., Yanofsky, R., Roy, A. C., De Vignemont, F., Culham, J. C., & Farné, A. (2021). The toolish hand illusion: Embodiment of a tool based on similarity with the hand. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-81706-6>
- Carello, C., Groszofsky, A., Reichel, F. D., Solomon, H. Y., & Turvey, M. (1989). Visually perceiving what is reachable. *Ecological Psychology*, 1(1), 27–54. <https://doi.org/10.1207/s15326969eco0101.3>
- Cignetti, F., Caudron, S., Vaugoyeau, M., & Assaiante, C. (2013). Body schema disturbance in adolescence: From proprioceptive integration to the perception of human movement. *Journal of Motor Learning and Development*, 1(3), 49–58. <https://doi.org/10.1123/jmld.1.3.49>
- Costello, M. C., & Bloesch, E. K. (2017). Are older adults less embodied? A review of age effects through the lens of embodied cognition. *Frontiers in Psychology*, 8. <https://doi.org/10.3389/fpsyg.2017.00267>
- Costello, M. C., Bloesch, E. K., Davoli, C. C., Panting, N. D., Abrams, R. A., & Brockmole, J. R. (2015). Spatial representations in older adults are not modified by action: Evidence from tool use. *Psychology and Aging*, 30(3), 656–668. <https://doi.org/10.1037/pag0000029>
- D'Angelo, M., Di Pellegrino, G., Seriani, S., Gallina, P., & Frassinetti, F. (2018). The sense of agency shapes body schema and peripersonal space. *Scientific Reports*, 8(1). <https://doi.org/10.1038/s41598-018-32238-z>
- De Vignemont, F., Ehrsson, H. H., & Haggard, P. (2005). Bodily illusions modulate tactile perception. *Current Biology*, 15(14), 1286–1290. <https://doi.org/10.1016/j.cub.2005.06.067>
- Di Pellegrino, G., & Làdavas, E. (2014). Peripersonal space in the brain. *Neuropsychologia*, 66, 126–133. <https://doi.org/10.1016/j.neuropsychologia.2014.11.011>
- Dotov, D. G., Nie, L., & Chemero, A. (2010). A demonstration of the transition from ready-to-hand to unready-to-hand. *PLoS One*, 5(3), Article e9433. <https://doi.org/10.1371/journal.pone.0009433>
- Farné, A., Iriki, A., & Làdavas, E. (2005). Shaping multisensory action–space with tools: Evidence from patients with cross-modal extinction. *Neuropsychologia*, 43(2), 238–248. <https://doi.org/10.1016/j.neuropsychologia.2004.11.010>
- Farné, A., & Làdavas, E. (2000). Dynamic size-change of hand peripersonal space following tool use. *Neuroreport*, 11(8), 1645–1649. <https://doi.org/10.1097/00001756-200006050-00010>
- García-Piqueras, J., García-Mesa, Y., Cárcaba, L., Feito, J., Torres-Parejo, I., Martín-Biedma, B., ... Vega, J. A. (2019). Ageing of the somatosensory system at the periphery: Age-related changes in cutaneous mechanoreceptors. *Journal of Anatomy*, 234(6), 839–852. <https://doi.org/10.1111/joa.12983>
- Gibson, J. J. (2014). The ecological approach to visual perception. In *Psychology Press eBooks*. <https://doi.org/10.4324/9781315740218>
- Head, H., & Holmes, G. (1911). Sensory disturbances from cerebral lesions. *Brain*, 34(2–3), 102–254. <https://doi.org/10.1093/brain/34.2-3.102>
- Holmes, N. P. (2012). Does tool use extend peripersonal space? A review and re-analysis. *Experimental Brain Research*, 218(2), 273–282. <https://doi.org/10.1007/s00221-012-3042-7>
- Holmes, N. P., Martin, D., Mitchell, W., et al. (2020). Do sounds near the hand facilitate tactile reaction times? Four experiments and a meta-analysis provide mixed support and suggest a small effect size. *Experimental Brain Research*, 238, 995–1009. <https://doi.org/10.1007/s00221-020-05771-5>
- Inoue, K., Kawashima, R., Sugiura, M., Ogawa, A., Schormann, T., Zilles, K., & Fukuda, H. (2001). Activation in the ipsilateral posterior parietal cortex during tool use: A PET study. *NeuroImage*, 14(6), 1469–1475. <https://doi.org/10.1006/nimg.2001.0942>
- Iriki, A., Tanaka, M., & Iwamura, Y. (1996). Coding of modified body schema during tool use by macaque postcentral neurones. *Neuroreport*, 7(14), 2325–2330. <https://doi.org/10.1097/00001756-199610020-00010>
- Jahanian Najafabadi, A., & Godde, B. (2025). Don't Try to Control Your Golf Club for Better Putting Performance. [https://doi.org/10.31219/osf.io/m4guh\\_v1](https://doi.org/10.31219/osf.io/m4guh_v1)
- Jahanian Najafabadi, A., Küster, D., Putze, F., & Godde, B. (2023a). Emergence of sense of body ownership but not agency during virtual tool-use training is associated with an altered body schema. *Experimental Brain Research*, 241(7), 1721–1738. <https://doi.org/10.1007/s00221-023-06644-3>
- Jahanian Najafabadi, A., Küster, D., Putze, F., & Godde, B. (2023b). Tool-use training in augmented reality: Plasticity of forearm body schema does not predict sense of ownership or agency in older adults. *Experimental Brain Research*, 241(7), 1739–1756. <https://doi.org/10.1007/s00221-023-06645-2>
- Jahanian-Najafabadi, A., Küster, D., Putze, F., & Godde, B. (2025). Task load affects tool embodiment during virtual tool-use in young and older adults. *Frontiers in Virtual Reality*, 6. <https://doi.org/10.3389/frvir.2025.1637212>
- Kalkert, A., & Ehrsson, H. H. (2012). Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience*, 6, 40. <https://doi.org/10.3389/fnhum.2012.00040>
- Kalkert, A., & Ehrsson, H. H. (2014). The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and Cognition*, 26, 117–132. <https://doi.org/10.1016/j.concog.2014.02.003>
- Kuroki, S. (2014). Anisotropic distortion in the perceived orientation of stimuli on the arm. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-021-93959-2>
- Làdavas, E., & Serino, A. (2008). Action-dependent plasticity in peripersonal space representations. *Cognitive Neuropsychology*, 25(7–8), 1099–1113. <https://doi.org/10.1080/02643290802359113>
- Longo, M. R. (2020). Tactile distance anisotropy on the palm: A meta-analysis. *Attention Perception & Psychophysics*, 82(4), 2137–2146. <https://doi.org/10.3758/s13414-019-01951-w>
- Longo, M. R., Azañón, E., & Haggard, P. (2009). More than skin deep: Body representation beyond primary somatosensory cortex. *Neuropsychologia*, 48(3), 655–668. <https://doi.org/10.1016/j.neuropsychologia.2009.08.022>
- Longo, M. R., & Haggard, P. (2011). Weber's illusion and body shape: Anisotropy of tactile size perception on the hand. *Journal of Experimental Psychology Human Perception & Performance*, 37(3), 720–726. <https://doi.org/10.1037/a0021921>
- Longo, M. R., & Lourenco, S. F. (2006). On the nature of near space: Effects of tool use and the transition to far space. *Neuropsychologia*, 44(6), 977–981. <https://doi.org/10.1016/j.neuropsychologia.2005.09.003>
- Longo, M. R., & Lourenco, S. F. (2007). Space perception and body morphology: Extent of near space scales with arm length. *Experimental Brain Research*, 177(2), 285–290. <https://doi.org/10.1007/s00221-007-0855-x>
- Mangalam, M., Fragaszy, D. M., Wagman, J. B., Day, B. M., Kelty-Stephen, D. G., Bongers, R. M., ... Osirak, F. (2022). On the psychological origins of tool use. *Neuroscience & Biobehavioral Reviews*, 134, Article 104521. <https://doi.org/10.1016/j.neubiorev.2022.104521>
- Mangalam, M., & Kelty-Stephen, D. G. (2020). Multiplicative-cascade dynamics supports whole-body coordination for perception via effortful touch. *Human Movement Science*, 70, Article 102595. <https://doi.org/10.1016/j.humov.2020.102595>
- Maravita, A., & Iriki, A. (2004). Tools for the body (schema). *Trends in Cognitive Sciences*, 8(2), 79–86. <https://doi.org/10.1016/j.tics.2003.12.008>
- Martel, M., Cardinali, L., Bertonati, G., Jouffrais, C., Finos, L., Farné, A., & Roy, A. C. (2019). Somatosensory-guided tool use modifies arm representation for action. *Scientific Reports*, 9(1). <https://doi.org/10.1038/s41598-019-41928-1>
- Martel, M., Cardinali, L., Roy, A. C., & Farné, A. (2016). Tool-use: An open window into body representation and its plasticity. *Cognitive Neuropsychology*, 33(1–2), 82–101. <https://doi.org/10.1080/02643294.2016.1167678>
- Martel, M., Cardinali, L., Roy, A. C., & Farné, A. (2017). Tool use unravels body morphology representation in the brain. In F. de Vignemont, & A. J. T. Alsmith (Eds.), *The subject's matter: The body and self-awareness*. Cambridge, MA: MIT Press.
- Martel, M., Finos, L., Koun, E., Farné, A., & Roy, A. C. (2021). The long developmental trajectory of body representation plasticity following tool use. *Scientific Reports*, 11(1). <https://doi.org/10.1038/s41598-020-79476-8>
- Melzack, R. (1997). Phantom limbs in people with congenital limb deficiency or amputation in early childhood. *Brain*, 120(9), 1603–1620. <https://doi.org/10.1093/brain/120.9.1603>
- Miller, L. E., Cawley-Bennett, A., Longo, M. R., & Saygin, A. P. (2017). The recalibration of tactile perception during tool use is body-part specific. *Experimental Brain Research*, 235(10), 2917–2926. <https://doi.org/10.1007/s00221-017-5028-y>
- Miller, L. E., Longo, M. R., & Saygin, A. P. (2014). Tool morphology constrains the effects of tool use on body representations. *Journal of Experimental Psychology Human Perception & Performance*, 40(6), 2143–2153. <https://doi.org/10.1037/a0037777>
- Noel, J., Blanck, O., & Serino, A. (2018). From multisensory integration in peripersonal space to bodily self-consciousness: From statistical regularities to statistical inference. *Annals of the New York Academy of Sciences*, 1426(1), 146–165. <https://doi.org/10.1111/nyas.13867>
- O'Shaughnessy, B. (1995). Proprioception and the body image. In J. L. Bermúdez, A. Marcel, & N. Eilan (Eds.), *The body and the self* (pp. 175–203). MIT Press.
- Osirak, F., De Oliveira, E., Navarro, J., & Reynaud, E. (2020). The castaway island: Distinct roles of theory of mind and technical reasoning in cumulative technological culture. *Journal of Experimental Psychology General*, 149(1), 58–66. <https://doi.org/10.1037/xge0000614>

- Pagano, C. C., & Day, B. (2020). Ecological interface design inspired by “the meaningful environment”. In J. B. Wagman, & J. J. C. Blau (Eds.), *Perception as information detection: Reflections on Gibson’s ecological approach to visual perception* (pp. 37–50). Routledge. <https://doi.org/10.4324/9780429316128>.
- Peviani, V., Melloni, L., & Bottini, G. (2019). Visual and somatosensory information contribute to distortions of the body model. *Scientific Reports*, 9(1). <https://doi.org/10.1038/s41598-019-49979-0>
- Raimo, S., Boccia, M., Di Vita, A., Cropano, M., Guariglia, C., Grossi, D., & Palermo, L. (2021). The body across adulthood: On the relation between interoception and body representations. *Frontiers in Neuroscience*, 15. <https://doi.org/10.3389/fnins.2021.586684>
- R Core Team. (2025). R: A language and environment for statistical computing. (version 4.5) [computer software]. Retrieved from <https://cran.r-project.org> (R packages retrieved from CRAN snapshot 2025-05-25).
- Rochat, P., & Wraga, M. (1997). An account of the systematic error in judging what is reachable. *Journal of Experimental Psychology Human Perception & Performance*, 23(1), 199–212. <https://doi.org/10.1037/0096-1523.23.1.199>
- Romano, D., Uberti, E., Caggiano, P., Cocchini, G., & Maravita, A. (2018). Different tool training induces specific effects on body metric representation. *Experimental Brain Research*, 237(2), 493–501. <https://doi.org/10.1007/s00221-018-5405-1>
- Ronga, L., Galigani, M., Bruno, V., Noel, J., Gazzin, A., Perathoner, C., Serino, A., & Garbarini, F. (2021). Spatial tuning of electrophysiological responses to multisensory stimuli reveals a primitive coding of the body boundaries in newborns. *Proceedings of the National Academy of Sciences*, 118(12). <https://doi.org/10.1073/pnas.2024548118>
- Sanz, C. M., Call, J., & Boesch, C. (2013). *Tool use in animals*. Cambridge University Press eBooks. <https://doi.org/10.1017/cbo9780511894800>
- Schettler, A., Raja, V., & Anderson, M. L. (2019). The embodiment of objects: Review, analysis, and future directions. *Frontiers in Neuroscience*, 13. <https://doi.org/10.3389/fnins.2019.01332>
- Schwoebel, J., & Coslett, H. B. (2005). Evidence for multiple, distinct representations of the human body. *Journal of Cognitive Neuroscience*, Apr;17(4), 543–553. <https://doi.org/10.1162/0898929053467587>
- Serino, A. (2019). Peripersonal space (PPS) as a multisensory interface between the individual and the environment, defining the space of the self. *Neuroscience & Biobehavioral Reviews*, 99, 138–159. <https://doi.org/10.1016/j.neubiorev.2019.01.016>
- Serino, A., Anella, L., & Avenanti, A. (2009). Motor properties of peripersonal space in humans. *PLoS One*, 4(8), Article e6582. <https://doi.org/10.1371/journal.pone.0006582>
- Serino, A., & Haggard, P. (2010). Touch and the body. *Neuroscience & Biobehavioral Reviews*, 34(2), 224–236. <https://doi.org/10.1016/j.neubiorev.2009.04.004>
- Shumaker, R. W., Walkup, K. R., Beck, B. B., & Burghardt, G. M. (2011). Animal tool behavior: The use and manufacture of tools by animals. *Choice Reviews Online*, 49(03), 49–1468. <https://doi.org/10.5860/choice.49-1468>
- Sirigu, A., Grafman, J., Bressler, K., & Sunderland, T. (1991). Multiple representations contribute to body knowledge processing. Evidence from a case of autotopagnosia. *Brain*, Feb;114(Pt 1B), 629–642. <https://doi.org/10.1093/brain/114.1.629>
- Sorrentino, G., Franza, M., Zuber, C., Blanke, O., Serino, A., & Bassolino, M. (2020). How ageing shapes body and space representations: A comparison study between healthy young and older adults. *Cortex*, 136, 56–76. <https://doi.org/10.1016/j.cortex.2020.11.021>
- Sposito, A., Bolognini, N., Vallar, G., & Maravita, A. (2012). Extension of perceived arm length following tool-use: Clues to plasticity of body metrics. *Neuropsychologia*, 50(9), 2187–2194. <https://doi.org/10.1016/j.neuropsychologia.2012.05.022>
- Sun, Y., & Tang, R. (2019). Tool-use training induces changes of the body schema in the limb without using tool. *Frontiers in Human Neuroscience*, 13. <https://doi.org/10.3389/fnhum.2019.00454>
- Sykes, J. J. (2023). Tools and peripersonal space: An enactive account of bodily space. *Phenomenology and the Cognitive Sciences*. <https://doi.org/10.1007/s11097-023-09903-4>
- The Jamovi Project. (2025). Jamovi. (version 2.7) [computer software]. Retrieved from <https://www.jamovi.org>.
- Tomasino, B., Weiss, P. H., & Fink, G. R. (2012). Imagined tool-use in near and far space modulates the extra-striate body area. *Neuropsychologia*, 50(10), 2467–2476. <https://doi.org/10.1016/j.neuropsychologia.2012.06.018>
- Tuitert, I., Golenia, L., Otten, E., Bootsma, R. J., & Bongers, R. M. (2020). Task constraints act at the level of synergies and at the level of end-effector kinematics in manual reaching and manual lateral interception. *Journal of Experimental Psychology. Human Perception and Performance*, 46(12), 1511–1526. <https://doi.org/10.1037/xhp0000861>
- Vaesens, K. (2012). The cognitive bases of human tool use. *Behavioral and Brain Sciences*, 35(4), 203–218. <https://doi.org/10.1017/s0140525x11001452>
- Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2005). Human cognition and 1/f scaling. *Journal of Experimental Psychology General*, 134(1), 117–123. <https://doi.org/10.1037/0096-3445.134.1.117>
- Viel, S., Vaugoyeau, M., & Assaiante, C. (2009). Adolescence: A transient period of proprioceptive neglect in sensory integration of postural control. *Motor Control*, 13(1), 25–42. <https://doi.org/10.1123/mcj.13.1.25>
- Vittersø, A. D., Halicka, M., Buckingham, G., Proulx, M. J., & Bultitude, J. H. (2019). Experimentally induced pain does not influence updating of peripersonal space and body representations following tool-use. *PLoS One*, 14(5), Article e0210045. <https://doi.org/10.1371/journal.pone.0210045>
- Witt, J. K. (2021). Tool use affects spatial perception. *Topics in Cognitive Science*, 13(4), 666–683. <https://doi.org/10.1111/tops.12563>
- Witt, J. K., Proffitt, D. R., & Epstein, W. (2005). Tool use affects perceived distance, but only when you intend to use it. *Journal of Experimental Psychology Human Perception & Performance*, 31(5), 880–888. <https://doi.org/10.1037/0096-1523.31.5.880>
- Zhang, J., & Hommel, B. (2015). Body ownership and response to threat. *Psychological Research*, 80(6), 1020–1029. <https://doi.org/10.1007/s00426-015-0698-1>