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Tool embodiment across the lifespan

Amir Jahanian Najafabadi [a,*], Alireza Rastegari [a], Matthew R. Longo [b]

[a] Department of Cognitive Neuroscience, Bielefeld University, Bielefeld, Germany
[b] School of Psychological Sciences, Birkbeck, University of London, United Kingdom

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ABSTRACT

Research has consistently shown that expertise in tool-use is associated with a phenomenon known as tool embodiment. Additionally, prior research has shown that higher ownership ratings over virtual tools in young adults are predicted by a reduction in perceived tactile distance of the forearm, whereas the sense of agency over virtual tools appears to arise independently of changes in perceptual estimation. In this study, we investigated whether the subjective ratings of ownership and agency over tools of different sizes used for grasping objects in both near and far space can be predicted by forearm tactile distance perception and perceived reaching distance (RDE). Additionally, we tested whether this embodiment process varies across the lifespan. Participants aged 12 to 80 years completed two experimental sessions using a well-established tool-use paradigm to manipulate objects in both near (within arm's reach) and far space (beyond arm's reach). A tactile distance judgment (TDJ) task was administered on the forearm in the proximodistal orientation. Subjective ratings of ownership and agency over the tool were collected through a post-task questionnaire. Results revealed significant effects of age and training space on ownership ratings, along with robust three-way interactions involving residual tactile distance estimation error and perceived reaching distance error. Overall, results revealed higher subjective ratings of ownership over the tool in adolescents and young adults compared to other age groups independent of training space. Results further revealed higher subjective ratings of ownership are significantly predicted by reduced forearm tactile distance estimation error in adolescents and young adults compared to middle-aged group in the far training condition. Higher ratings of agency over the tool were also significantly predicted by perceived forearm tactile distance interactively with training space conditions and age, however, effects were not significantly different dependent on age or training space condition. In addition, perceived reaching distance estimation error significantly predicted higher ratings of ownership and agency over the tool. More specifically, higher ratings of ownership were significantly predicted in adolescents and young adults compared to middle-aged adults in far space. For agency, however, higher ratings were predicted by perceived reaching distance independent of age or training space. Collectively, these results suggest that sensorimotor-based embodiment experiences, especially the extent that the ownership is perceived over the tool, are modulated by both perceived reaching distance and forearm tactile distance perception, with effects being most pronounced in adolescents and young adults.

1. Introduction

Expertise in tool-use is closely associated with tool embodiment, a phenomenon in which tools become integrated into the body representation through repeated use (Martel et al., 2016; Weser & Proffitt, 2021). Over time, tools are not merely perceived as external instruments but as extensions of the body. This integration enhances the experience of ownership (i.e., tool), the feeling that a tool is part of one's body, and agency, the sense of control over actions and their consequences (e.g., Gallagher, 2018, 2000). Sensorimotor experience contributes to shaping both the unconscious body schema, used for motor control, and the more conscious body image, which reflects beliefs about one's body (Paulus, 2014). These representations are shaped by sensory and motor experiences. Even short periods of tool-use can lead to measurable changes in how the body is perceived and structured mentally. Agency arises when intentional action is linked to a predictable outcome. Although this process develops early when individuals learn to control their limbs, it can transfer to external tools if there is a consistent relationship between

* Corresponding author.
E-mail address: amir.jahanian@uni-bielefeld.de (A. Jahanian Najafabadi).

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movement and sensory feedback (Chambon & Haggard, 2012; Haggard, 2017).

Tool-use has been shown to modify peripersonal space, defined as the space near the body available for interaction (Canzoneri et al., 2013; Iriki et al., 1996; Maravita & Iriki, 2004). The brain may remap far space into near space after tool-use training, which allows previously unreachable objects to be treated as reachable (De Vignemont & Iannetti, 2014; Martel et al., 2016; Weser & Proffitt, 2021). Such changes reflect a neural integration of tools into the body's action space (Cardinali et al., 2009, b; D'Angelo et al., 2018; Farnè et al., 2005). The extent of embodiment depends on several factors including age, type of movement (active vs passive/ voluntary vs involuntary), goal of movement (reaching vs grasping), similarity between tool and limb, tool size and shape, familiarity with the tool, and task load (Cardinali et al., 2021; Miller et al., 2014; Cardinali et al., 2016; Cardinali et al., 2009, b; Sposito et al., 2012; Jahanian-Najafabadi et al., 2025). Miller et al. (2014) demonstrated that morphological similarity between tool and effector influences representational plasticity. Training with a hand-shaped tool altered hand perception, whereas using an arm-like tool affected forearm perception. These findings suggest that representational changes are constrained by perceived similarity between body and tool.

1.1. Embodiment in virtual reality

Virtual reality (VR) has become a valuable platform for studying embodiment and body representation plasticity, offering precise control over variables such as movement synchrony and spatial congruity (D'Angelo et al., 2018; Jahanian Najafabadi et al., 2023a, 2023b; Jahanian Najafabadi, Botev, et al., 2025; Jahanian-Najafabadi et al., 2025; Ma & Hommel, 2015a, 2015b). Studies using virtual hands or virtual tools have shown that embodiment depends strongly on synchrony between the user's actions and the virtual effector. Ma and Hommel (2015b) proposed that virtual hand embodiment facilitates ownership and agency because it eliminates the need to establish ownership over an external object before agency occurs. D'Angelo et al. (2018) found that body schema and peripersonal space updating occur only when movements are synchronous. Moreover, whether space is perceived as expanding or contracting depends on the spatial location of the virtual effector. These findings suggest that body schema and peripersonal space are influenced by the relationship between intentional movement and expected spatial outcomes. Ownership has also been observed in VR during synchronous movement of a virtual limb and the user's real limb (Kokkinara & Slater, 2014; Tsakiris et al., 2010).

Additional evidence indicates that agency and ownership are dissociable. Mangalam et al. (2019) found that ownership emerged only when a rubber hand was placed in reachable space, whereas agency was experienced even when the hand was outside of reachable space. Mariano et al. (2024) also showed that spatial proximity, whether physically real or perceptually induced, is important for agency. These findings align with the idea of an affordance-based embodiment. Ownership is primarily grounded in bodily location and spatial constraints, while agency depends more on perceived agency and prediction, even at a distance.

Our earlier studies showed that young adults demonstrate body schema plasticity during virtual tool-use, while old adults do not (Jahanian Najafabadi et al., 2023a, 2023b). Ownership in young adults was linked to greater plasticity and stronger sensorimotor integration, whereas old adults showed agency without ownership, indicating a reduced flexibility in body representation with age. Moreover, task demand influenced embodiment differently across age groups. In young adults, mental load increased ownership, and physical load reduced agency over the virtual tool. Old adults were influenced mainly by performance-related demands (Jahanian-Najafabadi et al., 2025). Building upon these These findings led to the current real-world lifespan study using different tool sizes were conducted. The goal was to examine how ownership and agency relate to perceived tactile distance on the forearm and reaching distance both within and beyond arm's reach.

1.2. Ownership and agency across the lifespan

Tool-use requires a cohesive sense of self that can flexibly distinguish between internal and external components while integrating tools into the body schema (Bailenson & Yee, 2005; Hommel & Kibele, 2016). Although this flexibility persists into adulthood, its developmental trajectory and its dependence on biological and environmental factors remain unclear. Research suggests that children are more adaptable in integrating sensory signals and resolving mismatches between modalities (Della Longa et al., 2021; Lee et al., 2021). Adults rely more on cognitive strategies and stable sensory priors, which can influence motor performance and alter ownership and agency experiences (Liesner et al., 2021).

To master tool-use, individuals must learn to represent the body, tool properties, and location in space accurately. This process relies on multisensory integration, especially visual and proprioceptive cues. Visual information helps predict upcoming somatosensory events and supports sensorimotor adaptation (Kimura & Katayama, 2015, 2017, 2018). However, few studies have examined how ownership, agency, tactile distance perception, and reaching estimation interact across the lifespan.

Our previous augmented-reality study revealed that younger adults developed both agency and ownership when training to use a virtual tool, and ownership correlated with reductions in tactile distance estimation errors, indicating body schema plasticity (Jahanian Najafabadi et al., 2023a). In contrast, older adults achieved agency but did not show ownership or body schema updating (Jahanian Najafabadi et al., 2023b). These results suggest that body representation flexibility may decline with age and that agency can develop even without plastic changes to body schema.

Our recent lifespan study found no significant tool-use effects on body schema across age groups during near and far space training (Jahanian Najafabadi, Rastegari, et al., 2026). However, baseline differences were present. Adolescents showed higher tactile overestimation compared to younger, middle-aged, and older adults. This indicates that body representation develops rapidly during adolescence but becomes less adaptable later in life. Such findings propose that sensorimotor aging affects how the body is updated during tool-use, which has implications for rehabilitation and learning.

Further work showed that higher ownership ratings in young adults was associated with better performance and reduced tactile judgment errors, particularly with visuo-tactile feedback rather than vision alone (Jahanian Najafabadi et al., 2023a). Agency appeared even without body schema changes, suggesting that agency may be more resilient to alterations in sensory processing. Old adults showed agency but no ownership over the virtual tool, supporting a possible shift in cue integration. According to Moore et al. (2009) and Moore and Fletcher (2011), agency arises from weighted integration of internal motor cues and external sensory feedback. Costello and Bloesch (2017) proposed that old adults rely more heavily on visual cues, which may restrict peripersonal space updating and body schema plasticity. Our recent findings support this. In a golf-putting task, higher ratings of ownership and agency were linked to lower tactile estimation errors and more accurate reaching distnace estimates (Jahanian Najafabadi & Godde, 2025). Interestingly, participants with the best performance reported the lowest sense of agency, which suggests a complex relationship between strategy, motor confidence, and embodiment.

Further research revealed that cognitive and physical load influence embodiment differently across age groups. In young adults, mental load increased ownership and physical load reduced agency, while old adults showed weaker effects and were mainly affected by performance load (Jahanian-Najafabadi et al., 2025). In another study, we manipulated virtual gravitational physics and found that higher cognitive load reduced agency under high gravity, while ownership showed a minor increase under cognitive effort, possibly due to greater engagement with the virtual environment (Jahanian Najafabadi, Botev, et al., 2025).

1.3. Tactile distance judgment test as a measurement of body schema

Over the years, the tool-use paradigm has become a widely accepted and ecologically valid approach for studying body representational plasticity, motor control, and movement kinematics (e.g., Cardinali et al., 2009, b; Cardinali et al., 2012; Farnè et al., 2005; Maravita & Iriki, 2004). Previous research has primarily focused on participants' ability to perform tool-related tasks with precise movements in both distance and direction to examine the impact of aging on sensorimotor processing and body schema plasticity (Caçola et al., 2014). As the tool-use paradigm gains prominence in body representation studies, the accuracy in the perception of tactile distances and tactile localization across different body parts, particularly the forearm, has been increasingly linked to the construction of metric body representation. The idea that tactile distance perception is a fundamental component of body schema processing—and essential for constructing an accurate mental representation of the body—supports the use of the tactile distance judgment task (TDJ) as a reliable method for investigating body schema plasticity and its associated somatosensory processing (e.g., de Vignemont et al., 2005; Longo, 2020). Since then, TDJ has been employed in various study designs (e.g., Jahanian Najafabadi et al., 2023a, 2023b; Jahanian Najafabadi, Botev, et al., 2025; Jahanian-Najafabadi et al., 2025; Miller et al., 2014; Miller et al., 2017; Sun & Tang, 2019) to explore how tool-use training influences body schema, particularly concerning hand as the primary effector used to interact with tools.

In contrast to many previous studies that assessed tactile distance on different body parts or orientations (e.g., Jahanian Najafabadi et al., 2023a, 2023b; Miller et al., 2014; Miller et al., 2017), the present study employed a TDJ task in which participants estimated the distance between two tactile stimuli applied to the forearm in a proximodistal orientation. This choice was informed by our prior research, which found no significant effects when the stimuli were presented in the mediolateral orientation (Jahanian Najafabadi et al., 2023a). Because participants are not explicitly asked to reflect on their body or body representation, this task serves as an implicit measure. It reveals how tool-use can alter somatosensory perception, highlighting the dynamic interplay between tool-use, body schema, and sensory processing, and how external tools become incorporated into the body's representation.

The core hypothesis linking tool-use to body representation rests on a clear mechanistic prediction: If a change in the internal body map is the mechanism for adapting motor control and kinematics after tool-use, then the size of the objective change in body representation must be proportionally related to the kinematic change (for review; Bell & Macuga, 2022). This prediction suggests that the degree of plastic change measured by TDJ and reaching distance estimation (RDE) errors should correlate directly with the strength of subjective tool embodiment. For instance, participants with shorter relative arm lengths might experience a relatively larger extension of the arm representation when a given tool is used, engendering a greater subsequent change in kinematics and stronger embodiment signals. Establishing this correlation between the size of the change in body and spatial representations and the strength of the subjective/behavioral change (i.e., tool embodiment) is crucial for confirming that body representation is the underlying mechanism for tool-use adaptation, rather than just an indirect consequence of it (e.g., Martel et al., 2016; Miller et al., 2014).

1.4. Current study

An underestimation of the distance perceived on the arm indicates a shortened arm in the body schema, which again can be interpreted as an addition of the tool to the arm within the borders of the neural sensorimotor representation (Jahanian Najafabadi et al., 2023a). Building on previous research, in this study, we first tested whether the sense of ownership and agency emerge and whether that emergence varies based on the participants' act and produce an outcome in near and far space i.e., reaching, grasping and moving objects using a grabber. We further explored whether the sense of ownership and agency over tools of different sizes can be predicted by perceived forearm tactile distance perception and perceived reaching distance. Additionally, we aimed to replicate our prior findings across various age groups. The extent of the perceived reaching distance estimation is measured using a reaching distance estimation task (RDE, Witt et al., 2005; Bourgeois et al., 2014; D'Angelo et al., 2018; Jahanian Najafabadi & Godde, 2025). Under control conditions, participants tend to overestimate how far they can reach (Bourgeois et al., 2014). Decreased overestimation after tool-use training was suggested to indicate remapping of the far space to the near space due to embodiment of a tool (Maravita & Iriki, 2004). We hypothesize that **(1)** subjective BO ratings will be higher when participants use a shorter tool in Near Space compared to a longer tool in Far Space. **(2)** subjective BA ratings will be consistently high and will not significantly differ based on age or spatial context, reflecting the agency's basis in motor control. **(3)** higher BO ratings will be predicted by reduced TDJ and RDE errors, and this predictive effect will be significantly stronger in adolescents and young adults than in middle-aged and older adults, particularly in the Far Space training condition. **(4)** the predictive power of TDJ and RDE errors on BA ratings will be stable across age groups and spatial contexts, with no significant age-related differences in prediction, suggesting agency's resilience to body schema changes. **(5)** Middle-aged and older adults will show weaker predictive associations between body metric errors (TDJ/RDE) and subjective BO and BA ratings compared to adolescents and young adults. These predictions stem from the understanding that age-related differences in sensory integration and accumulated experience with tool-use may lead to the adaptation of alternate strategies for body representation re-mapping under the tool-use influence (Jahanian Najafabadi & Hommel, 2025; Martel et al., 2021).

To test these hypotheses, participants from different age groups completed two experimental blocks using tools of varying sizes to retrieve objects from either near or far spaces. TDJ and RDE tasks were administered before and after each training block, with results previously reported in Jahanian Najafabadi et al. (2026). Explicit ownership and agency were collected via self-report questionnaires rated by participants after each training session, and these ratings were analyzed in relation to changes in tactile and spatial perception across all age groups, as presented in this study.

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., Miller et al., 2014; Bahmad et al., 2020) 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

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)

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 to measure RDE and TDJ. Following this, participants engaged in five blocks (each 12 trials) of tool-use training where they used either a 30 cm or 70 cm mechanical grabber to reach 60 objects located at 80 cm and 120 cm, respectively. This was followed by a post-test for the first session where the RDE task and TDJ were carried out by the experimenters and continued by asking participants to answer to the questionnaire (please see section 2.6), including 12 questions to rate the sense of ownership (BO) and sense of agency (BA) over the tool. 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 the first session, except that in this session, participants used a mechanical grabber with a length that was not used in the first session. In the continuation of 5 blocks of trials, post-test evaluations were carried out in the same way as the post-test assessments of the first session, including TDJ and RDE tasks, along with a questionnaire for perceived BO and BA over the tool. Details of the experimental design for both training sessions are presented in Fig. 1.

2.3. 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 was 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

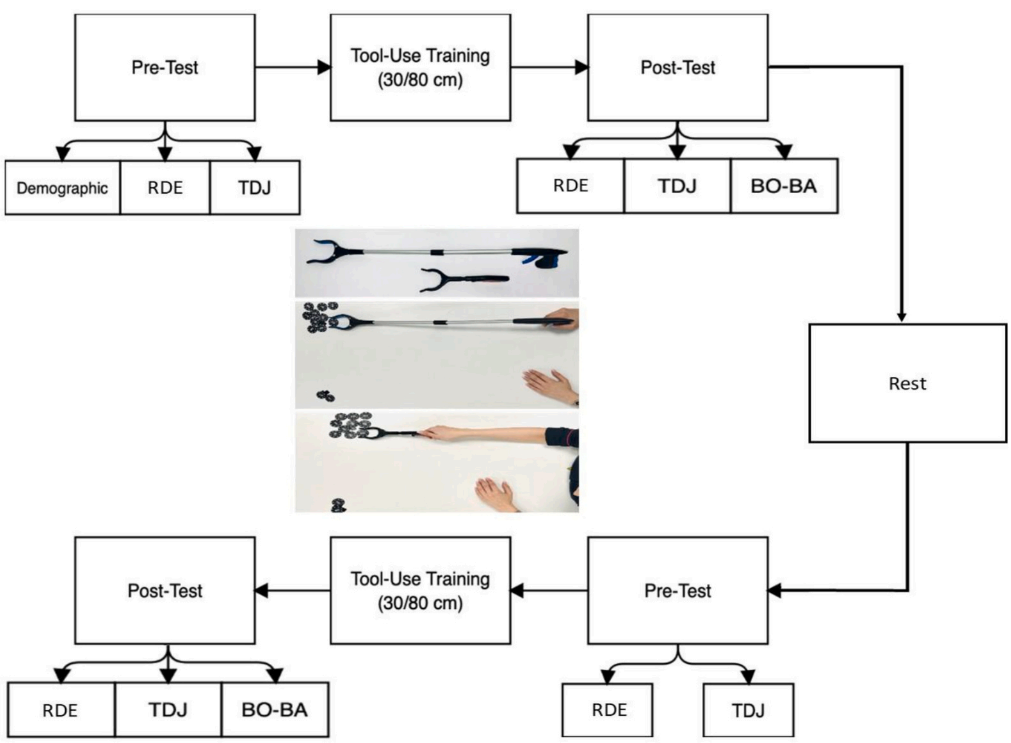

Fig. 1. Schematic of the experimental procedure across two counterbalanced tool-use sessions. Each session included pre- and post-tests, during which three measures were collected: reaching distance estimation (RDE), tactile distance judgment (TDJ), and subjective ownership and agency (BO/BA). Participants completed tool-use training with either a short or long mechanical grabber, and the order of tool type was randomized across participants. In the pre-test, RDE was administered first, followed by TDJ. In the post-test, measures were collected in the following sequence: TDJ, RDE, and BO/BA.

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. 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). Under control conditions, participants tend to overestimate how far they can reach (Bourgeois et al., 2014). A small ball (40 mm in diameter), controlled by the experimenter through a linear actuator, moved toward 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 distance reaching, i.e., when they would be able to last/first reach the ball 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 at hand 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.

2.6. Measures of ownership and agency

To assess ownership and agency, we employed the BO and BA questionnaire developed by Kalckert and Ehrsson (2012, 2014) and used by Zhang and Hommel (2015) and in our previous virtual tool-use studies (Jahanian Najafabadi et al., 2023a, 2023b; Jahanian Najafabadi, Botev, et al., 2025; Jahanian-Najafabadi et al., 2025). This questionnaire, as outlined in Table 2, involved the assessment of various

Table 2
Statements used in the ownership and agency questionnaire (adapted from Zhang & Hommel, 2015).

Variable	Statement
BO	**Q1:** I felt as if the tool was an extension of my own hand
	Q2: I felt as if the tool was part of my body
	Q3: I felt as if the tool was my hand
BO-related	**Q4:** It seemed as if I had more than one right hand
	Q5: It felt as if my right hand no longer mattered, as if I only needed to sense the tool
	Q6: I felt as if my real hand developed an enhanced sense of touch
BA	**Q7:** I felt as if I could cause movements of the tool
	Q8: I felt as if I could control movements of the tool
	Q9: The tool was obeying my will, and I could make it move just like I wanted it to
BA-related	**Q10:** I felt as if the tool was controlling my movements
	Q11: It seemed as if the tool had a will of its own
	Q12: I felt as if the tool was controlling me

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

statements through a 7-point Likert scale, with responses ranging from −3 indicating "strongly disagree" to +3 denoting "strongly agree". While in the original version, each statement was scored on a 7-point Likert scale; in this study to avoid bias and control the responses given by participants, for each item they received a bar which was labeled as strongly disagree and strongly agree at each of the tips (−50, +50 mm). Participants were asked to put a marker at any location of the bar that they felt closer to their perceived BO or BA, depending on each questionnaire item. In our opinion, using a rating line from − + 50 for measuring BO and BA can offer certain advantages over traditional Likert scales has two advantages (for reviewGrünbaum & Christensen, 2020; Kuhlmann et al., 2017; Wenke et al., 2009). Firstly, the − + 50 scale allows for a more nuanced and precise measurement of participants' perceptions and experiences compared to the Likert scales, which typically have fewer response options (e.g., 7-point scales). This finer granularity can capture subtle changes and variations in BO and BA perceptions, particularly in the context of tool-use where subtle differences may be important. Secondly, the use of a continuous analogue scale allows participants greater flexibility in expressing their opinions and experiences compared to the Likert scales, which present fixed response options. This can lead to more accurate and individualized responses, as participants are not constrained by predefined categories.

For statistical purposes, as suggested by previous studies (e.g., Zhang & Hommel, 2015) four mean scores were computed by combining responses to three questions each: Questions 1 to 3 focused on the perception of one's hand as their own, denoted as BO while questions 7 to 9 directly addressed intentional agency experiences, referred to as BA. Questions 4 to 6 (BO-related) and 10 to 12 (BA-related) have been used as related items to validate the core embodiment experiences while detecting misattribution or over-attribution, which is crucial for understanding the strength and nature of embodiment effects (Zhang & Hommel, 2015). Responses to questions 10 to 12 were reverse-coded due to their nature of questioning loss of agency over the tool. As per Kalckert and Ehrsson (2012, 2014), a mean score exceeding +1 was interpreted as indicating the presence of BO and BA. In this study, we transformed scores to equivalent responses like the original version and made it eligible for statistics and comparison. For further analysis we omitted the related items as they are used exclusively to control items starting section 3.2.2.

3. Statistical analysis

3.1. Data preparation and analysis

Statistical analyses were carried out using Python (version 3.12) and statistic-related libraries. The current investigation aimed to assess whether participants' subjective ratings of body ownership (BO) and body agency (BA), collected after each tool-use training block, could be predicted by estimation errors in tactile distance judgment (TDJ) and reaching distance estimation (RDE). These estimation errors were treated as indicators of the degree to which the tool was incorporated into the body schema and whether the representation of space extended beyond the arm's natural reach. The TDJ and RDE measures used in this study were drawn from a broader dataset that has been analyzed and presented in detail in our previous study (Jahanian Najafabadi et al., 2026). That prior analysis includes comprehensive information on baseline adjustment procedures and residual calculation using General Linear Modeling (GLM). In the present work, we used the residuals from that earlier study, representing post-training errors, not explained by baseline performance or target distance, as predictors in new models focused on BO and BA. In these analyses, BO and BA ratings were treated as outcome variables in separate models. Residual TDJ and RDE errors were entered as continuous predictors. The purpose of this approach was to examine the extent to which individual differences in TDJ were reflected in these residuals, and RDE accounted for variation in participants' reported sense of ownership and agency over the tool.

Consistent with the principle that the most informative metric in embodiment studies is the comparison between conditions, all inferential statistical analyses, including linear regressions, correlation analyses, and mixed-effects models, were conducted using the continuous, absolute mean scores for BO and BA. This approach preserves the full variance of the participants' ratings and avoids reliance on the binary threshold, thereby directly addressing potential concerns regarding subjective rating biases. Additionally, prior to conducting inferential analyses on the Residual TDJ Error, we assessed the assumption of homogeneity of variance across the four Age Groups (Adolescents, Young Adults, Mid-Age Adults, Old Adults) using Levene's test. The test indicated a significant violation of this assumption, confirming heteroscedasticity across the groups ($F(3, 601) = 4.55$, $p = .003$). As detailed in the descriptive statistics (cf. Fig. 4), the Adolescent group displayed substantially greater variability (heteroscedasticity) in TDJ errors compared to the adult cohorts. Consequently, we interpreted the results cautiously and, where applicable, employed robust estimation techniques to account for this violation.

3.2. Results

3.2.1. Sense of ownership and agency over the tool

For Ownership ratings, General Linear Modeling (GLM) revealed a significant overall effect of the model ($F(15, 664) = 3.43$, $p < .001$). Additionally, significant effects of Age Group on Ownership ratings ($F(3, 664) = 7.61$, $p < .001$), and a significant effect of Training Space ($F(1, 664) = 8.31$, $p = .003$), indicating that higher level of Ownership experience over the tool was partially affected by both age and Training Space. However, Residual TDJ Error did not alone predict higher Ownership ratings ($F(1, 664) = .673$, $p = .41$).

Additionally, there was a significant three-way interaction effect between Age Group × Training Space × Residual TDJ Error ($F(3, 664) = 3.01$, $p = .029$). Post-hoc analysis showed that the negative association between Ownership ratings and Residual TDJ Error (i.e., higher ownership was associated with reduced tactile distance estimation) was conditional on Age Group and Training Space. Specifically, this relationship was most prominent in the Far Space condition and contributed to the subsequent group differences reported below. Post-hoc comparisons focusing only on Age Group differences within the same Training Space predicted by reduced Residual TDJ Error showed that, in the Far Space condition, Ownership ratings over the tool were significantly higher for AD compared to MA (Mean Difference = 17.32; SE = 4.69; $t(664) = 3.69$, $p = .006$, Cohen's $d = 0.6$). Similarly, YA also reported higher Ownership ratings compared to MA in Far space (SE = 4.27; $t(664) = 3.67$, $p = .006$, Mean Difference = 15.65, Cohen's $d = .54$). No significant differences were found between OA and other groups in the Far condition ($p > .05$). Fig. 3 illustrates overall mean ratings for ownership and agency over short and long tools across Age Groups and Training Space.

No statistically significant differences were found between OA trained in Near versus Far space ($t(664) = .86$, $p = .99$, *Cohen's* $d = .14$), and no significant comparison effect was found across other Age Groups at Near or Far Space. Results indicate that AD and YA consistently reported the highest levels of Ownership, particularly in both Far and Near training spaces. In contrast, the OA group reported lower ownership ratings across both conditions when compared to other groups. These findings suggest that the effect of Training Space on Ownership ratings predicted by reduced Residual TDJ Error is more pronounced in AD and YA compared to MA groups, and OA appears less sensitive to spatial condition in shaping Ownership experiences.

For Agency ratings, the overall model was statistically significant ($F(15, 664) = 3.39$, $p < .001$). Results revealed significant effect of Age Group ($F(3, 664) = 2.8$, $p = .04$), and significant effect of Training Space on Agency ratings ($F(1, 664) = 8.57$, $p = .004$), Age Group × Training Space ($F(1, 664) = 7.5$, $p = .006$), and significant interaction effect of Age Group × Residual TDJ Error ($F(3, 664) = 6.29$, $p < .001$) suggesting

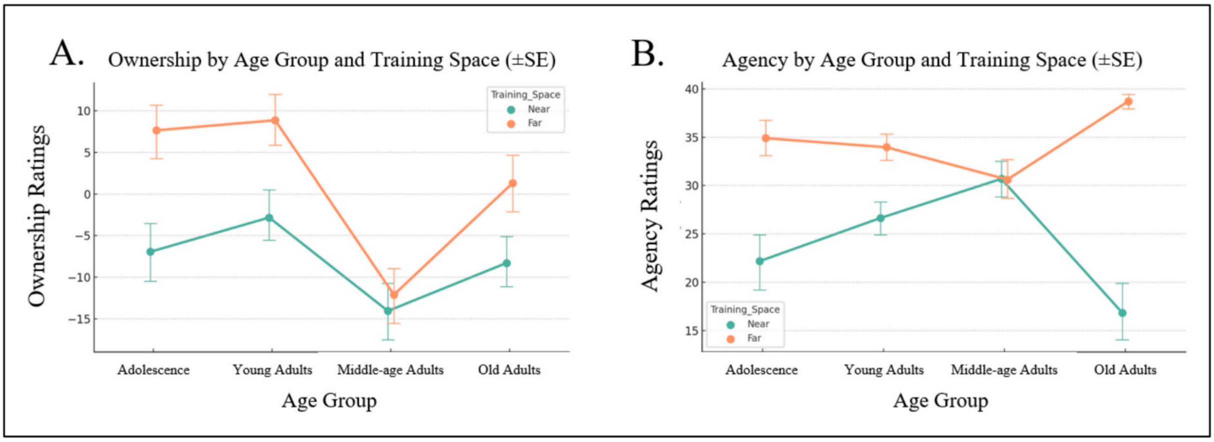

Fig. 3. Overall Mean Ownership **(A)** and Agency ratings **(B)** over the Short and Long Tools across Age Groups and Training Space. Error bars represent +-SE and solid lines represent Mean values.

that Agency ratings differed depending on whether participants were trained in Near or Far space. We further observed a significant interaction effect between Age Group × Training Space × Residual TDJ Error (F (3, 664) = 4.78, p = .003).

Post-hoc comparisons further revealed in the Far Training Space, no statistically significant differences were observed among Age Groups. Comparisons between AD, MA, YA, and OA all yielded non-significant results ($p > .05$). For instance, the comparison between AD and MA resulted in a difference of 2.88 (t = 0.701, p = .997), while YA versus MA showed a difference of −4.11 (t = −1.099, p = .957). These findings

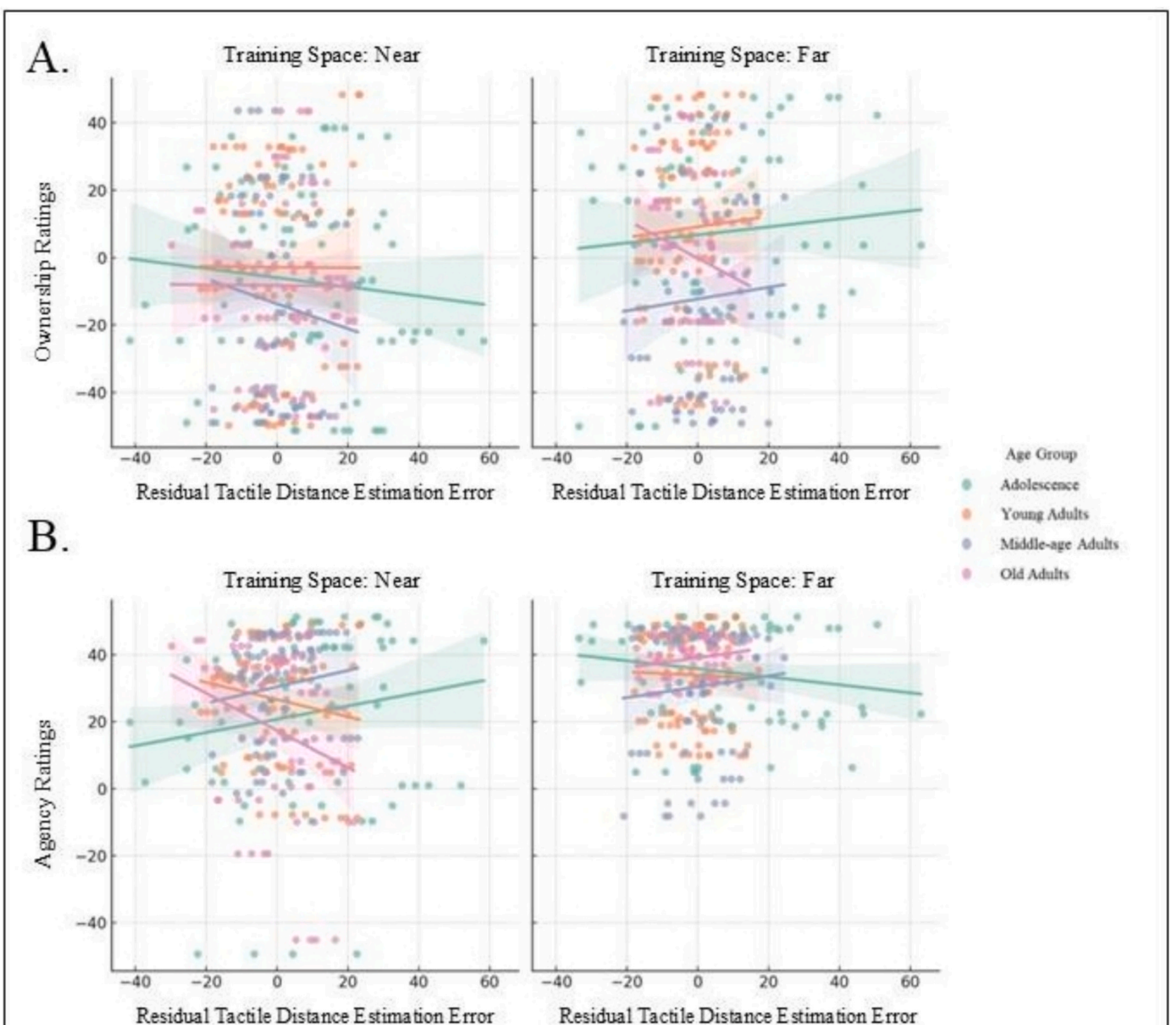

Fig. 4. Mean Ownership **(A)** Agency ratings **(B)** over the Short and Long Tools at Near and Far Training Space across Age Groups for Residual Tactile Distance Estimation Error (TDJ Error in mm).

indicate that performance in the Far condition was relatively consistent across all age groups, with no group demonstrating a statistically reliable advantage or disadvantage. Similarly, in the Near Training Space, no significant age-related differences were detected ($p > .05$).

The largest observed difference was between MA and OA, with a mean difference of 10.30; however, this difference did not reach statistical significance ($p = .197$). All other pairwise comparisons within the Near condition, including those between YA and MA or AD and MA, were also non-significant, with *p*-values greater than 0.30. Fig. 4 illustrates overall mean ratings for ownership and agency over the Short and Long Tools at Near and Far Training Space across Age Groups for Residual Tactile Distance Estimation Error.

GLM was further conducted for Ownership ratings as the dependent variable, Training Space and Age Groups as factors, and Reaching Distance Estimation Error (RDE Error) as a covariate. Results revealed a significant effect of Age Group on Ownership ratings ($F(3, 664) = 10.22$, $p < .001$), as well as marginal significant effect of Training Space ($F(1, 664) = 6.7, p = .01$), Age Group × Training Space ($F(3, 664) = 2.23, p = .08$). However, RDE Error alone was not a significant covariate ($F(1, 664) = .02, p = .886$). A significant interaction effects of the Age Group × RDE Error ($F(3, 664) = 4.92$, $p = .002$), and a robust three-way interaction between Age Group × Training Space × RDE Error ($F(3, 664) = 14.8, p < .001$) were observed, suggesting that overall RDE Error significantly predicted higher Ownership ratings over the tool depending on Age and Training Space.

Post-hoc tests revealed that AD and YA consistently reported significantly higher Ownership ratings compared to MA within the Far Space condition (AD vs. MA: *Mean Difference* = 21.78*, SE* = 4.47*, t* = 4.87*, p* < .001, *Cohen's d* = 0.78; YA vs. MA: *Mean Difference* = 19.34, *SE* = 4.10, *t* = 4.71, *p* < .001, *Cohen's d* = .69). Other Far Space comparisons, including AD vs YA and comparisons involving OA, did not reach statistical significance (*all p > .05*). In the Near Space condition, the largest difference, AD vs MA, showed a moderate effect size (*Mean Difference* = 10.43), but did not reach significance ($p = .310$). Other comparisons (e.g., YA vs MA, OA vs MA) all yielded *p > .05*. Our significant results replicate the trend that AD and YA show significantly higher Ownership ratings predicted by reduced perceived RDE Error compared to MA in Far Space condition, however, AD and YA did not differ significantly, suggesting comparable levels for these groups.

For Agency ratings, the overall GLM model was significant ($F(15, 664) = 4.41, p < .001$). RDE Error significantly predicted higher Agency ratings over the tool ($F(1, 664) = 8.63, p = .003$), Age group ($F(3, 664) = 2.54$, $p = .05$), and Age Group × RDE Error ($F(3, 664) = 3.61$, $p = .013$). While the main effect of Training Space was not statistically significant ($F(1, 664) = 2.67$, $p = .103$), we observed a significant three-way interaction between Age Group × Training Space × RDE Error ($F(3, 664) = 6.67, p < .001$) suggesting the overall predictive effect of RDE Error depending on Age and Training Space condition leading to increased Agency experiences over the tool.

In addition, a post-hoc comparisons further showed no significant Age Group differences in the Near and Far conditions ($p > .05$), indicating age group ratings were relatively equivalent under Near-space conditions. Fig. 5 further illustrates (A) Ownership and (B) Agency ratings over the two tools (Short and Long) for Reaching Distance Estimation Error (RDE Error) depending on each Age Group.

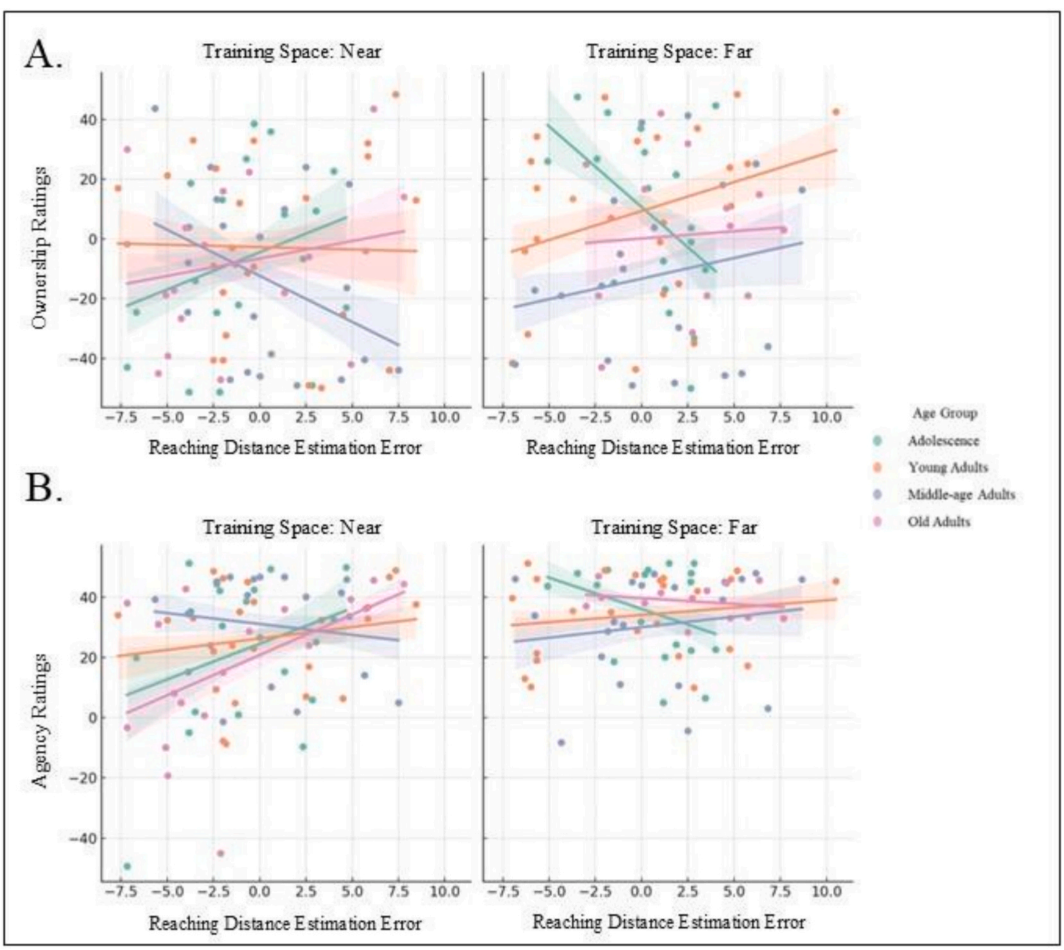

Fig. 5. Mean Ownership **(A)** and Agency ratings **(B)** over the Short and Long Tools at Near and Far Training Space across Age Groups for Reaching Distance Estimation Error (RDE Error in cm).

3.2.2. Sense of ownership and agency over tools of different sizes

As an additional analysis to assess whether participants experienced a sense of ownership and agency over the short/long tool during each training session, we calculated the mean and standard error (SE) of their subjective ratings. These ratings were analyzed to determine whether participants' experiences fell below or exceeded the threshold established in previous research (Kalckert & Ehrsson, 2012, 2014).

Descriptive analyses across age groups and tool lengths revealed distinct patterns in ownership (BO) and agency (BA) ratings (see Table 3). Adolescents showed higher BO and BA scores with long tools compared to short tools. Young adults also reported increased BO and BA ratings with long tools, particularly for agency. Middle-aged adults had overall lower BO ratings regardless of tool length, while their BA ratings remained high and stable. Old adults demonstrated reduced BO ratings across both tool lengths but retained moderate to high BA scores, especially with long tools. These findings suggest a developmental trajectory where agency remains preserved across age, even as ownership sensitivity may decline. Given the above results, only the mean values for BA and BA-related, but not BO and BO-related, were above **1** and thus above the threshold suggested by Kalckert and Ehrsson (2012, 2014). Fig. 6 illustrates BO and BA ratings depending on the tool size and across age groups.

3.2.3. Association of ownership and agency ratings with TDJ estimation error and RDE error depending on training space

To examine whether BO and BA ratings were influenced by tactile distance estimation error and spatial training conditions, we conducted a series of ANCOVAs using Residual Estimation Error (TDJ Error) and Reaching Distance Estimation Error (RDE Error) as predictors. Analyses were performed separately for each BO and BA as a dependent variable.

In each analysis, the predictors included TDJ Error, RDE Error, Age Group, Training Space, and their interactions. This included main effects, two-way and three-way interactions: Predictor × Age Group × Training Space. The Residual TDJ Error was derived from a two-step correction procedure: post-training estimation errors were regressed against baseline performance and target TDJ stimulus distances. The residuals represented recalibrated perceptual error, independent of baseline or task constraints. Negative residuals indicate reduced estimation error after tool-use training, showing improved tactile distance estimation administered on their forearm.

To ensure robustness, we removed statistical outliers using interquartile range filtering within each Age Group × Training Space cell for all key measures. ANCOVA was conducted, and significance thresholds were set at $p < .05$. Where significant three-way interactions were observed, we decomposed effects using subgroup-specific simple slope analyses (i.e., separate regressions per Age Group × Training Space combination). These analyses identified which interactions exhibited the strongest predictive effects. Notably, several dependent variables demonstrated significant three-way interactions, suggesting that the predictive power of TDJ or RDE error on subjective ratings varied with both age and spatial training conditions. In such cases, we observed, for example, that young adults trained in the Far space exhibited stronger associations between reaching estimation error and agency experience. These effects were supported by model summaries, correlation coefficients, and visualized in stratified regression plots by Age Group and Training Space, which we detail in the following sections.

4. Discussion

In this study, we investigated whether the emergence of subjective experiences of ownership and agency over a physical tool varies with tool size (correspond to near vs. far space) and age. We also examined whether these experiences could be predicted by forearm tactile distance perception and perceived reaching distance. Participants from different age groups completed two experimental sessions using a well-established tool-use paradigm (Cardinali et al., 2009, b; Cardinali et al., 2012; Miller et al., 2014; Miller et al., 2017), during which they grasped and relocated objects in near and far spaces toward their body. First, we re-analyzed data from Jahanian Najafabadi et al. (2026) to assessed tool-use induced representational plasticity, as measured by tactile distance judgments and perceived reaching distance across training blocks and spatial conditions. We then examined whether residual estimation errors in these measures predicted subjective ratings of ownership and agency. Finally, we explored how these ratings were modulated by training condition (tool size and spatial context) and whether associations with tactile and reaching perception differed across near and far space.

4.1. Summary of findings

In this study, the sense of ownership did not emerge during tool-use training given the threshold in subjective ratings (Kalckert & Ehrsson, 2012, 2014), however, results revealed significant effects of age and training space on ownership ratings, along with robust three-way interactions involving residual tactile distance estimation error and perceived reaching distance error. Overall, we observed higher ratings of ownership over the tool in adolescents and young adults compared to other age groups independent of training space. Results further revealed higher ratings of ownership is significantly predicted by reduced forearm tactile distance estimation error in adolescents and young adults compared to middle-aged group in far training condition. Higher ratings of agency were also significantly predicted by perceived forearm tactile distance interactively with training space conditions and age; however, effects were not significantly different depending on age or training space condition. In addition, perceived reaching distance estimation error significantly predicted higher ratings of ownership and agency. More specifically, higher ratings of ownership were significantly predicted by reduced perceived RDE Error in adolescents and young adults compared to middle-aged adults in far space. For agency, however, higher ratings were predicted by perceived reaching distance independent of age or training space. Collectively, these results suggest that sensorimotor-based embodiment experiences, especially the extent that the ownership is perceived over the tool, is modulated by both perceived reaching distance and forearm tactile distance perception, with effects being most pronounced in adolescents and young adults. These components consistently serve as predictors across groups, the observed differences suggest distinct neural and/or behavioral mechanisms that shape the emergence of agency during tool-use training.

The predictive relationship observed in the adolescent group should

Table 3
Descriptive statistics of ownership (BO) and agency (BA) ratings across age groups and tool lengths. Means and standard errors (SE) are presented in parentheses.

Age Group	Tool-Length	BO	BO-related	BA	BA-related
Adolescents	Short	−6.94 (3.33)	−2.74 (3.20)	22.18 (2.94)	13.36 (3.55)
	Long	4.93 (3.43)	−0.26 (3.43)	30.61 (2.73)	25.57 (2.61)
Younger Adults	Short	−7.36 (2.95)	−7.50 (2.28)	18.77 (2.70)	22.71 (2.84)
	Long	3.06 (2.99)	−5.20 (2.54)	25.06 (2.74)	25.66 (2.84)
Mid-Age Adults	Short	−16.20 (3.21)	−23.90 (2.21)	26.15 (2.51)	26.10 (2.62)
	Long	−14.00 (3.24)	−23.60 (2.53)	26.70 (2.64)	31.90 (2.47)
Older Adults	Short	−7.67 (3.33)	−5.53 (3.16)	17.62 (2.94)	15.46 (2.87)
	Long	−2.96 (2.84)	−3.04 (2.88)	24.84 (3.17)	18.84 (2.67)

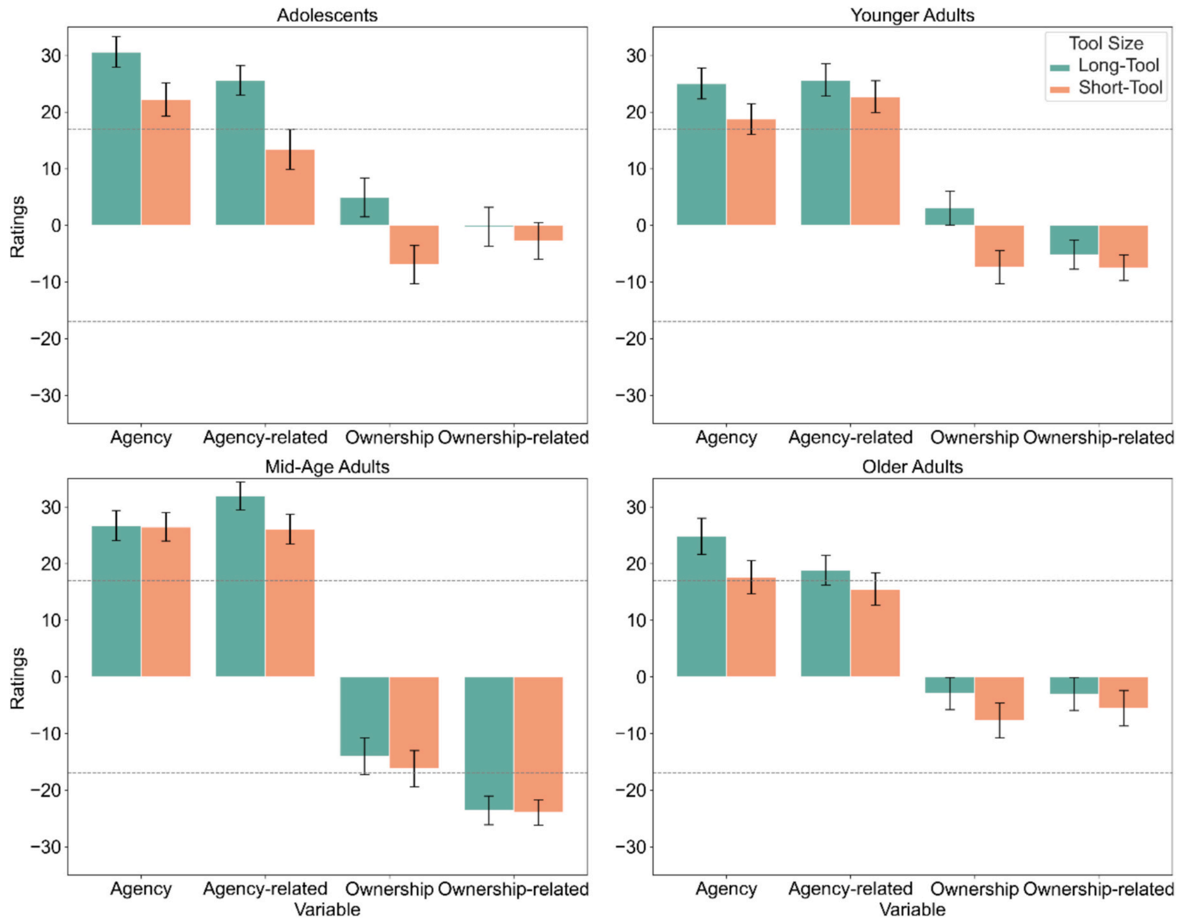

Fig. 6. Ratings of BO, BO-related, BA, and BA-related subscales for adolescents, young adults, mid-age, and old adults depending on Tool Size (short vs long). Dashed lines indicate the descriptive threshold (+1). Bars represent group means, and error bars show the standard error of the mean (SE).

be interpreted in light of this cohort's distinctive descriptive pattern. Levene's test confirmed that TDJ error variance was significantly higher in adolescents than in the adult cohorts, confirming heteroscedasticity. We interpret this elevated variability as reflecting the developmental instability and ongoing reorganization of the body schema during adolescence, a period characterized by heightened sensorimotor plasticity (Martel et al., 2016). This instability is expressed as greater fluctuation in the implicit metrical representation of the forearm, as captured by the TDJ task. Methodologically, the larger variance observed in adolescents offered sufficient statistical range to reveal a meaningful predictive relationship between subjective embodiment and implicit representational plasticity. By contrast, the lower and more stable variance in young and middle-aged adults likely constrained the detection of similar effects within those groups, suggesting that reduced variability in body-related metrics may mask underlying associations in more mature populations.

4.2. *Age-specific pattern of predictive effects of ownership ratings*

When comparing different age groups, our data showed that the predictive effect of tactile distance estimation and perceived reaching distance for ownership ratings declines with age. This pattern was evident in the post-hoc analysis that showed adolescents and young adults have higher ratings of ownership in comparison to middle-aged adults in far space. In older adults, this decline was so pronounced that neither of our statistical models reached significance. Notably, the sense of ownership did not emerge during tool-use training in any age group, regardless of training space, and that reproduces findings presented by our previous studies for young and older adults (Jahanian Najafabadi et al., 2023a, 2023b). Despite the non-emergence of the ownership feeling, perceived reaching distance remained a significant predictor of higher ownership ratings in far-space training compared to near-space across adolescents and younger adults' groups but not among older age participants. Interestingly, a similar age-related pattern emerged when analyzing the predictive effect of tactile distance estimation on ownership ratings. These age-specific patterns highlight the complex interplay between different components of body representation and suggest distinct developmental trajectories across age groups. Despite the significant importance of this developmental view as a key to understanding the underlying processes for body representation plasticity, this subject remains largely unexplored, with only a few studies aiming to emphasize the dissociation of these different body representation components over the lifespan (Brozzoli et al., 2009; Cardinali et al., 2009, b; Martel et al., 2021). We speculate that adolescents and young adults may more readily adapt their sensorimotor boundaries, enabling tools used in far space to be more easily incorporated into the body representation. This developmental sensitivity likely reflects greater neuroplasticity and flexibility in body representation during these stages of life. Prior research has shown that multisensory integration as a foundation of body ownership continues to mature throughout childhood and adolescence (Cowie et al., 2013; Gori et al., 2008), suggesting that younger individuals are better equipped to integrate external objects into their bodily representations. These findings align with the “malleable body schema” hypothesis proposed by Cardinali et al. (2009, b), which suggests that individuals with more flexible or still-developing body maps are more capable of updating internal representations through tool-use. This view is further supported by Blanke et al. (2015), who emphasized that the neural systems underlying bodily self-consciousness continue to develop during adolescence, potentially enhancing the capacity for embodiment-related plasticity during this period.

In light of this, the effect of age on the balanced integration of sensory information and forward prediction of the action's consequence was also described in neurological studies. For instance, Wolpe et al. (2016) suggested that sensory attenuation happens as a result of the complicated integration of afferent information with the action's predictions stemming from internal movement models. As we age, attenuation amplifies in proportion to the reduction in the sensitivity to the sensory information, evident by the findings of alterations in both structure and functional connectivity of the pre-supplementary motor area (pre-SMA). This reduction in the sensitivity to the sensory information could be interpreted as the sign of more resilient internal models in older individuals.

4.3. Age-specific pattern for sense of agency

Although the sense of agency over the tool was reported across all age groups and tool sizes with no significant differences based on age or training space, higher agency ratings were significantly predicted by perceived forearm tactile distance, in interaction with both age and training context. Additionally, perceived reaching distance estimation error emerged as a robust predictor of agency, regardless of participants' age or the tool-use condition. One of the most striking differences is that, unlike ownership, the sense of agency emerged over the tool in all age groups, regardless of updates in body representation and perceived reachability. This aligns with our previous study (Jahanian Najafabadi et al., 2023a, 2023b), which suggests that motor learning for tool mastery can occur independently of bodily representation updates and the emergence of ownership.

Although the age-dependency hypothesis was not supported in the case of agency, and agency over the tool was experienced independently of perceived forearm tactile distance, a closer examination of the underlying processes suggests that embodiment and sense of agency are not solely determined by the integration of sensory inputs. Rather, in our opinion it also depends on how different sensory components are weighted in shaping the final experience. For instance, the visual system plays a critical role in generating predictive information about the timing, location, and nature of expected somatosensory events, thereby influencing agency-related processes (Kimura & Katayama, 2015, 2017, 2018). This highlights the importance of visual-somatosensory integration in the brain's ability to process and anticipate sensory information from the environment. Our results further confirm prior findings (Jahanian Najafabadi et al., 2023a, 2023b) where participants experienced higher sense of agency over the tool independent of changes in forearm tactile distance perception and that effects are not significantly different in young and older adults.

With aging, the reduced flexibility of spatial and bodily representations may limit the extent to which tools become integrated into the sensorimotor representation. Prior research has shown that body schema remains highly adaptable in adolescence due to rapid bodily changes during puberty (Cardinali et al., 2009, b; Martel et al., 2021), whereas in old adults, cognitive decline and reduced sensorimotor plasticity may constrain these adaptive processes (Jahanian Najafabadi et al., 2023b). Prior findings suggested that the extent of this integration may depend on the individual's capacity for bodily adaptation (Bell & Macuga, 2022; Cardinali et al., 2009, b; De vignemont & Farne, 2010). While younger individuals may incorporate tools more readily due to greater change in forearm tactile distance estimation, older adults may experience limitations in this process. Future research should further investigate whether prolonged training or alternative tool-use paradigms can facilitate tool embodiment across different life stages.

4.4. Mechanistic link: body representation as the driver of adaptation

A central challenge in embodiment research is explaining how changes in body representation translate into behavioral adaptation. We propose a mechanistic perspective that plastic changes in body representation (indexed by RDE and TDJ errors) serve as the primary causal mechanism driving subsequent adaptations in action following tool-use. In this view, the subjective experience of ownership and agency reflects a readout or consequence of these underlying neural and somatosensory changes, providing the essential evidence for our mechanistic claim.

To move beyond descriptive developmental trends, we propose that the relationship between implicit changes in body representation and subjective embodiment is mediated by recalibration of internal sensorimotor models through multisensory integration. Perceived reaching distance (RDE) reflects the functional extension of peripersonal space and informs the brain's forward model for action prediction. When RDE error indicates successful peripersonal space expansion, the internal model accurately predicts sensory outcomes of tool-use, strengthening the sense of agency. In groups where this recalibration is incomplete (e.g., mid-age adults), prediction errors weaken subjective agency. While perceived forearm tactile distance (TDJ) reflects the metrical body schema, ownership arises from multisensory congruence, integrating visual feedback and somatosensory input. Larger TDJ errors indicate greater plastic distortion of the body schema toward the tool, supporting the subjective feeling of ownership. Age-related declines in this predictive link suggest reduced multisensory reweighting and diminished capacity for body schema adaptation in older adults. In sum, RDE changes drive functional action prediction and agency, while TDJ changes drive metrical body schema updates and ownership, providing a mechanistic explanation for the age- and context-dependent patterns observed in our study.

Across age groups, RDE generally showed clearer and more context-sensitive links to embodiment than tactile body-schema shifts (measured by TDJ). This suggests that the functional adaptation of peripersonal space plays a more central and consistent role as a mechanistic driver of subjective body awareness. Furthermore, the greater variability in TDJ among adolescents aligns with the developmental instability and heightened plasticity of the body schema in this age group, providing the statistical range necessary to observe the strongest objective-to-subjective correlations.

Our results indicate that the magnitude and variability of body representation changes are not uniform across the lifespan. For example, the heightened predictive power of perceived forearm tactile distance and perceived reaching distance errors specifically in adolescents aligns with the idea that individuals with highly plastic and rapidly changing body maps experience larger functional adaptations. This increased objective change strengthens the association between plasticity markers and subjective embodiment, confirming that body representation actively mediates the adaptation process in this cohort. The strong link between perceived reaching distance error, which indexes peripersonal space extension, and the sense of agency experienced during tool-use indicates that the feeling of control is fundamentally tied to the brain's ability to accurately map its action space and predict sensory consequences (Haggard, 2017). Effective tool-use requires rapid recalibration of the sensorimotor system's internal forward model (Maravita & Iriki, 2004). Perceived reaching distance provides an objective readout of this recalibration: higher RDE error indicates that the internal model has successfully incorporated the tool's extension (Canzoneri et al., 2013). Subjective agency then reflects the congruence between predicted and actual outcomes. In groups where this recalibration is weaker, such as middle-aged adults, the internal model may fail to fully integrate the tool, producing mismatches between expected and actual sensory feedback. This decoupling explains why RDE changes are less predictive of agency in these groups.

Perceived forearm tactile distance error, which reflects distortions in forearm perception, is closely tied to the metrical body schema (Longo, 2020). The subjective sense of ownership emerges from multisensory congruence, integrating visual feedback about the tool with the internal body map (Tsakiris, 2009). The magnitude of TDJ error serves as an objective marker of how much the somatosensory map has plastically adapted toward the tool (Miller et al., 2014). Greater distortions correspond to a stronger signal that the tool is integrated into the structural body representation. Age-related declines in predictive strength suggest that older adults have reduced precision and weighting of somatosensory inputs during multisensory integration (Jahanian Najafabadi et al., 2023b; Miller et al., 2014), limiting the capacity for body schema plasticity and weakening the link to ownership.

Overall, the observed age-dependent relationships demonstrate that the degree of plastic change in perceived forearm tactile distance and reaching distance errors predicts the magnitude of subjective experience of tool embodiment. These findings, in our opinion, provide strong quantitative evidence that changes in body representation are likely mechanistic drivers of tool-use adaptation, rather than mere correlates, highlighting the functional role of both peripersonal space expansion and body schema recalibration in shaping embodiment across the lifespan.

4.5. Limitation and future direction

A limitation of our design is the fixed order of the dependent measures (RDE always administered before TDJ). While this sequence was chosen for conceptual consistency, minimizing cross-task contamination (i.e., protecting RDE from potential sensory adaptation induced by TDJ), it prevents a definitive assessment of task order effects. Crucially, we maintain the validity of our conclusions because our primary findings rely on differential effects (changes between conditions, spaces, and age groups). Any systematic order effect would apply equally to all comparison groups, effectively canceling out when calculating these differences. We recommend that subsequent studies employing both RDE and TDJ use a fully randomized or counterbalanced design to explicitly evaluate the influence of task order on the magnitude and interrelationship of these body representation measures. Moreover, to confirm the underlying sensorimotor integration, future research should incorporate objective measures of ownership, such as proprioceptive drift or changes in thermal perception, which are less susceptible to self-report bias. Additionally, exploring methods to increase the intensity and duration of visuomotor feedback could help facilitate the emergence of ownership across the lifespan.

5. Conclusion

In conclusion, both reaching distance estimation and tactile distance judgment emerged as reliable predictors of the sense of agency and enhanced ownership over a tool, even in the absence of measurable plasticity in body representation typically induced by tool-use. However, the strength of these predictive relationships varied depending on participants' age and the spatial context of training. These findings suggest that the way we incorporate tools into our sense of self changes with age, shaped by evolving body representation, spatial perception, and movement awareness—though notably, the sense of agency over the object e.g., tools remain more stable across development. Crucially, our quantitative evidence elevates changes in reaching distance estimation and tactile distance judgment from mere correlates to likely mechanistic drivers of tool-use adaptation, highlighting the functional roles of both peripersonal space expansion and tool-induced body schema recalibration across the lifespan. Further research is needed to better understand the developmental and neurocognitive mechanisms underlying these patterns, and to clarify how perceptual feedback informs the internal models that support body–space integration.

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 Collection. **Matthew R. Longo:** Writing – review & editing, Validation.

Ethic statement

This study was approved by the Ethics Committee of the Bielefeld University (EUB-2023-120-S).

Financial statement

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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 via Tool Embodiment Across the Lifespan. Alternatively, data can bre requested via email to the corresponding author.

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