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Task load affects tool embodiment during virtual tool-use in young and older adults

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Introduction: Prior research revealed that after virtual tool use training, younger as compared to older adults, experienced a higher sense of tool-ownership over virtual tools associated with changes in sensorimotor representation (i.e., body schema). Moreover, higher agency ratings over the tool were independent of their performance levels and the extent to which the virtual tool was integrated into their arm representation. In contrast, older adults exhibited an increased sense of agency, which was strongly associated with improvements in virtual tool use performance. Regardless, no changes to their body schema, and no emergence of a sense of ownership were revealed in older adults.
Methods: Comparing data from a questionnaire and an analogue scale as two subjective measurements of embodiment during and after virtual tool-use training, we investigated whether this tool embodiment in both age groups could be predicted by task load assessed with the NASA TLX where participants rated their perceived task load related to the tool-use task in six dimensions (mental, physical, temporal, effort, performance and frustration). Data from 34 younger and 39 healthy older adults were analyzed.
Results: Results revealed that in younger adults, mental load led to increased ownership ratings over the virtual tool, and physical load negatively affected the sense of agency. Older adults showed weaker effects, with performance load being the only significant predictor of higher agency ratings. Further analyses of the analogue scale, which was embedded as an interactive probe in the experiment, provided novel fine-grained data on perceived sense of control during the training. Our results highlight robust age-related differences in tool-use performance, with younger adults consistently completing tasks more quickly than older adults. Sense of control, captured through the embedded analogue scale, significantly predicted faster performance, whereas ownership ratings did not contribute to timing performance. Agency ratings alone were not predictive, but their relationship with performance varied across age groups, suggesting that different mechanisms may underlie perceived agency in younger and older participants.
Discussion: Taken together, these findings indicate that while age strongly influences tool-use efficiency, subjective experiences of control and agency also shape performance, underscoring the value of incorporating multiple measures of embodiment for a comprehensive understanding of virtual tool use.

KEYWORDS

task load, virtual embodiment, visuo-tactile feedback, agency, ownership, tool-use, healthy aging

1 Introduction

The sense of agency experienced during voluntary actions arises from a combination of sensory predictions and various inferences. It refers to the experience that one's own actions or their outcomes are generated by oneself—that one is the source and initiator of the action (Gallagher, 2000; 2018). It thus involves a pre-reflective awareness that "I am the origin of this movement," whether the movement occurs voluntarily or involuntarily, and is often expressed as the feeling of being in control over one's actions (Tsakiris et al., 2009). For instance, when individuals use a tool to grasp a distant object and assess their level of control, their perception of control and agency are shaped by the local correlations between motor commands and visual or visual-tactile feedback, as well as by the overall outcome of the performed action, i.e., whether it succeeds or fails (e.g., Rognini et al., 2013). The same principle applies when tool use is studied in virtual environments, such as augmented reality (AR), where contributions of visual and visual-tactile feedback may be more systematically disentangled (Jahanian Najafabadi et al., 2023a). The relative weight given to sensory predictions versus sensorimotor feedback can vary depending on the context and the perceived reliability of the available cues. Recent research by Charalampaki et al. (2023) found that mismatches in tactile information significantly reduced the sense of agency, similar to the effects of spatial and temporal mismatches reported in the literature. These findings highlight the crucial role of tactile information in shaping the experience of voluntary action in experimental studies and are aligned with previous research emphasizing the importance of tactile information in motor control (see, e.g., Moscatelli et al., 2019). In this line, as reported by prior research (Sherman et al., 1998; Dewey, 2023; Hon et al., 2013), when task load increases and impairs performance, it may also reduce the sense of agency because limited working memory makes it harder to predict and monitor actions, especially during new tasks, which can also be influenced with age (Savage et al., 2019), which has also been reported in our prior studies (Jahanian Najafabadi et al., 2023b).

The sense of ownership is another key concept for studying tool embodiment. It relates to the perceptual experience that one's body belongs to oneself—a feeling of "mineness" toward bodily states, sensations, or thoughts (Braun et al., 2018; Tsakiris, 2010; 2017). It is the distinction between what is perceived as part of one's own body versus external objects or the bodies of others, and it depends on context, arising when one is directly engaged in a given condition but absent in another (Tsakiris, 2010; Tsakiris et al., 2009). Ownership reflects the perception that specific body parts are part of one's own body, accompanied by the awareness that "I am the one who will undergo this experience," such as when the body moves regardless of whether the movement is voluntary or involuntary (Gallagher, 2000). As for work on tool-use representational plasticity, work on tool use and its incorporation into the somatosensory system has studied the use of real physical tools and it's morphological similarity (e.g., Miller et al., 2014; Cardinali et al., 2009, 2011), whereas more recent work has begun to shift the focus to virtual environments (D'Angelo et al., 2018). Interestingly, a recent study (Qu et al., 2021) using a virtual hand illusion paradigm revealed that heightened task load increased the sense of ownership and agency in explicit measures, but reduced them in implicit measures. This suggests that explicit and implicit measures rely on partly distinct informational sources, while the distinction between ownership and agency appears less significant.

In a recent study (Jahanian Najafabadi et al., 2025), the impact of different gravitational physics on virtual tool embodiment was investigated to understand whether various types of task load predict the emergence of ownership and agency. Results demonstrated a strong negative correlation between cognitive load and agency ratings, particularly in the high-gravity condition, indicating that higher cognitive demands reduce participants' perceived control over the virtual environment. Mental load, temporal load, effort, and frustration levels significantly contributed to this decline in agency, with frustration having the most pronounced impact. Interestingly, while increased task load generally diminished agency, marginally significant positive correlations between mental and temporal load and ownership ratings suggest that higher cognitive effort may, in some cases, enhance the sense of ownership over the virtual controller. This implies that, depending on the gravitational condition, as users invest more cognitive resources, they may feel more integrated into the virtual environment, though this effect was weaker compared to the influence on agency.

In a recent study, Pastel et al. (2022) investigated how different types of body visualization in virtual reality (VR) affect motor task performance in younger (18–30 years) and older adults (55 years and older). Participants completed balance, grasping, and throwing tasks in both VR and real-world settings, while their performances were evaluated under varying conditions of body visualization. The study assessed completion time, number of steps, perceived task difficulty, errors, and movement quality. Their results revealed that the absence of visible body parts in VR significantly reduced movement quality, though this effect was not observed in older adults. Across both VR and real-world conditions, older adults performed significantly worse than the younger age group. In VR, both groups required more time, rated the tasks as more difficult, and showed reduced performance quality compared to a real-world setting. These findings suggested that while older adults are capable of performing basic motor tasks in VR, task demands should be carefully considered, and body visualization appears less critical for this age group than for younger adults.

While previous studies have utilized tool-use paradigms to explore various aspects of cognitive embodiment in healthy aging (see Jahanian Najafabadi et al., 2023a; Jahanian Najafabadi et al., 2023b), to the best of our knowledge, no study has directly compared the phenomenon of virtual tool embodiment in visuo-tactile modalities between younger and older adults. This gap in research is particularly compelling, as it aligns with the intriguing notion that the sense of agency during tool-use might be a construct of the conscious mind affected by task load, a concept that remains untested. This perspective leaves a critical gap in our understanding of how older adults, compared to younger adults, process and integrate multisensory feedback under conditions of increased mental effort. Virtual tool embodiment, which involves experiencing and interacting with objects in virtual environments as extensions of one's own body, offers significant potential for advancing our understanding of sensorimotor integration and cognitive processes in healthy aging populations. Addressing this gap could provide valuable insights into the interplay between cognitive resources, sensory predictions, and motor control in the

aging brain, offering both theoretical contributions and practical applications for designing age-friendly virtual tools and rehabilitation technologies.

1.1 Current study

In this study, we aimed to explore whether task load during a visuo-motor sequential task, particularly tool-use training, influences participants' experience of a sense of ownership and agency over virtual tools in AR, depending on two distinct training conditions: one involving vision-only feedback and the other incorporating visuo-tactile feedback. To address this objective, task load during virtual tool-use training was assessed with the NASA Task Load Index (TLX) assessment (Hart and Staveland, 1988). Participants evaluated their experiences of ownership and agency after training with a questionnaire adopted from Kalckert and Ehrsson (2012), Kalckert and Ehrsson (2014) and Zhang and Hommel (2015) as described in own previous research (Jahanian Najafabadi et al., 2023a; Jahanian Najafabadi et al., 2023b; Jahanian Najafabadi et al., 2025). Sense of control over the virtual tool during training was assessed with a measurement tool consisting of a virtual slider integrated into the AR environment, where participants rated their sense of control over the tool on an embedded analogue scale immediately after completing a set of trials during each training block. Our aim for embedding this scale was to include a more fine-grained measure of current experience of Sense of Control, and to reduce potential memory biases (Mauss and Robinson, 2009). We thus designed the visual-analogue rating as an embedded probe (see Corrigan et al., 2014) that used the immediate virtual task environment to avoid any breaks in the user experience (Putze et al., 2020). First, we hypothesized that higher task load should decrease participants' sense of agency and overall tool embodiment, with visuo-tactile feedback potentially mitigating this effect to some extent. Second, we further hypothesized that increased task load may lead to a reduced sense of agency over the tool in older compared to younger adults, suggesting an age-dependent effect. In line with prior research using motor tasks (e.g., Pastel et al., 2022), the time duration for the completion of each tool use trial was recorded. Additionally, we investigated how age, feedback modality, and subjective embodiment affect tool-use performance, as measured by time reduction during tool-use training. Third, we hypothesized that a stronger sense of embodiment (subjective control over the tool) would predict improved tool-use performance, as reflected in greater time reduction where the required time in each trial is considered as a measurement of performance (Wen et al., 2015). Additionally, we expected that younger adults would show greater time reduction than older adults, and that feedback modality (visual vs. visuo-tactile) might further modulate performance with a stronger effect during tool use training with visuo-tactile feedback.

2 Methods

2.1 Participants

For this study, we re-analyzed and extended data of thirty-four young (15 males, 19 females; Mage: 23.64, SD: 7.07) and thirty-nine older (22 males, 19 females, Mage: 68.92, SD: 4.49), healthy and right-handed adults who previously participated in our studies on tool-use training in augmented reality (Jahanian Najafabadi et al., 2023a; Jahanian Najafabadi et al., 2023b; Jahanian Najafabadi et al., 2023c). Young and older adults were recruited from the student pools at the University of Bremen and Constructor University Bremen, as well as a cohort of families living in Bremen-Nord, Germany, respectively. Each participant was compensated with 10 Euros per hour. Participants had normal-to-corrected vision with no known history of neurological abnormality or disease, provided informed consent, and were naive to the experimental hypothesis, acuity, and errors. In this work, we extended our previous research on embodiment by re-analyzing existing datasets, incorporating task load, timing performance and slider (sense of control) measurements to deepen our understanding and address our hypothesis more comprehensively. All subsequent analyses' procedures were approved by the Ethics Committee of the University of Bremen (06/03/2018), and were in accordance with the principles of the Declaration of Helsinki.

2.2 Study design

Participants underwent a virtual tool-use training in AR in training blocks with and without vibro-tactile feedback as described in the training section below. All procedures of this study were reported in our previous studies by Jahanian Najafabadi et al. (2023a), Jahanian Najafabadi et al. (2023b), Jahanian Najafabadi et al. (2023c). Both ownership and agency ratings for the virtual tool were assessed with questionnaires after the first and second training blocks. As the focus of this paper is on the subjective measurement of ownership and agency and the question of whether there is an association with the emergence of ownership and agency over the virtual tool and task load reported by the questionnaire, we will report only findings from the ownership and agency, slider and NASA TLX assessments. Table 1 presents the detailed steps that participants performed to complete the task, and measurements were conducted.

2.3 Virtual tool-use training in augmented reality

Participants sat in front of a white table, wearing a Meta2 AR headset (www.metavision.com), which included earphones for receiving verbal instructions. A wireless HTC Vive Tracker 2. 0 model KLIM was attached to the back of their right hand. Next, participants donned a special glove (CyberTouch-II, CyberGlove System Inc., 2157 O'Toole Ave, San Jose, USA) on their right hand. The CyberTouch-II provides fine-grained vibro-tactile feedback on the inside of each finger and the palm. This glove further records the finger movement. The vibrational frequency generated from the CyberTouch-II ranges from 0 to 125 Hz with a total of 6 vibrotactile actuators: one on the inside of each finger, and one on the palm. Vibrational amplitude is 1.2 N peak-to-peak at 125 Hz (max). Sensor resolution is 1°, sensor repeatability is 3°, and sensor data rate is 90 records/sec.

The experimental AR tool-use training task was implemented in Unity (version 2018.3.8f1), and featured a virtual gripper tool

TABLE 1 Study design.

Tool use training block 1 (visual/visuo-tactile)	Post-test	Tool use training block 2 (visual/visuo-tactile)	Post-test
120 trials Measurements: Timing performance and sense of control	Ownership & Agency Questionnaires, NASA-TLX	120 trials Measurements: Timing performance and sense of control	Ownership & Agency Questionnaires, NASA-TLX

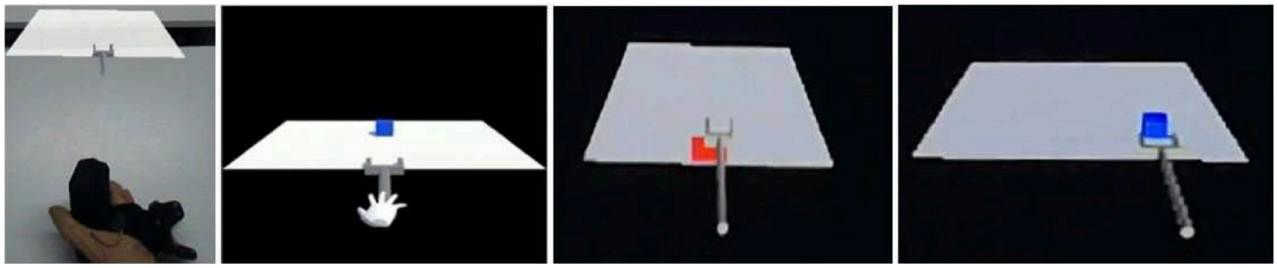

FIGURE 1
Virtual tool use paradigm and experiment scene.

consisting of two parallel legs connected to an elongated stick and a blue cube as the target object that the participant had to enclose with the legs of the gripper tool (See Jahanian Najafabadi et al., 2023a; Jahanian Najafabadi et al., 2023b; Jahanian Najafabadi et al., 2023c for experimental setup). In addition to the AR environment generated in Unity, participants could see the real surface of the table and their hands which was overlaid by the virtual hand. The end of the stick was virtually attached to the hand.

This setup ensured that the virtual environment was matched to the corresponding physical elements, allowing participants to experience the paradigm in a spatially congruent way.

The virtual tool was modeled in Unity in a way that when overlaid with the physical table in physical space, its length equated to about 30 cm in the real reaching space of participants when placed at the starting position in front of the participant. Given a forearm length of 25 cm (flat on the physical table), all cubes in the virtual space could be reached. This estimate is not perfectly precise because the apparent size of the entire scene was influenced by the exact distance of the projection screen to the eyes of the participant, which in turn could be modulated by the tightness of fit for the device. However, these differences were minimal. Furthermore, the relative proportions of the virtual scene (including the tool, the plane, and the objects therein) were fixed and thus equally affected by any such (small) variations (cf., Figure 1).

Participants performed two blocks of virtual tool-use training, one block with a visual and vibro-tactile feedback condition and one block with only a visual feedback condition. Each block consisted of 120 trials in two half blocks, and the order of blocks was randomized among participants. During training, to start a trial, participants first had to place their hands at a central starting position before them, as indicated by a red square. The distance to the red square was kept constant. The blue target cube then appeared at different locations in the plane in front of the participants. Participants had to move their hand, and thus, the virtual gripper, towards the object to grasp it. The task was to enclose the virtual object with the gripper without touching either side or moving the gripper into the object. In the condition with tactile feedback, touching the object resulted in vibratory feedback to either the thumb (touched left), the index finger (touched right), or the palm (touched at front). Timing performance was operationalized as time reduction. Each trial had a maximum duration of 20 s. A trial ended once the object was correctly enclosed by the gripper and the participant returned their hand to the start position to initiate the next trial. For analysis, the duration taken to complete the trial was subtracted from the maximum trial duration (20 s). Thus, larger values indicated greater time reduction, reflecting faster and more efficient task performance.

Participants were informed in advance that an error would occur if they touched (or moved) inside the cube for more than 2 s or if they touched the cube with the tool's left or right sides for more than 2 s. Then the trial would fail and end.

After 10 consecutive trials, there were 10 s of rest. After each half block of 60 trials, there was 1 minute of rest. After the first block (i.e., in the middle of the experiment), approximately 10 min of rest were granted. Before each condition started and during the 1-min break after the first 60 trials, participants were alerted about the type of feedback. Before training, participants performed 20 practice trials to learn how to control the virtual tool by moving their right hand, forward, backward, left, or right. The size of the target cube was 40 mm^3. Each training half block of 60 trials started with maximally open gripper jaws (120% percent of the cube size, i.e., 48 mm^3). Gripper size was then changed adaptively by decreasing the width of the tool in steps of 0.4 mm in a 3 down/1 up staircase procedure. This is to approach a stable 79.4% correct performance level over the practice trials (Leek, 2001).

2.4 Ownership and agency questionnaire

To measure ownership and agency, we adopted the ownership and agency questionnaire from prior research (Kalckert and Ehrsson, 2012; 2014; Zhang and Hommel, 2015; Jahanian

TABLE 2 Statements used in the ownership and agency questionnaire (adapted from Zhang and Hommel, 2015; Jahanian Najafabadi et al., 2023a; Jahanian Najafabadi et al., 2023b). Abbreviations: BO (Body Ownership); BO-related (Body Ownership-related); BA (Body Agency); BA-related (Body Agency-related).

Variable	Statement
BO	Q1: I felt as if the virtual tool was an extension of my own hand
	Q2: I felt as if the virtual tool was part of my body
	Q3: I felt as if the virtual tool was my hand
BO-related	Q4: It seems 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 virtual tool
	Q6: I felt as if my real hand developed an enhanced sense of virtual touch
BA	Q7: I felt as if I could cause movements of the virtual tool
	Q8: I felt as if I could control movements of the virtual tool
	Q9: The virtual 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 virtual tool was controlling my movements
	Q11: It seemed as if the virtual tool had a will of its own
	Q12: I felt as if the virtual tool was controlling me

Najafabadi et al., 2023a; Jahanian Najafabadi et al., 2023b) (cf. Table 2). Each statement was scored on a 7-point Likert scale (−3 "strongly disagree" to +3 "strongly agree"). Four mean scores were calculated for statistical analysis by aggregating 3 questions each: Q1-Q3 were about the experience of perceiving the hand as one's own hand, i.e., ownership and Q7-Q9 were directly associated with the experience of intentional control, i.e., agency. "ownership-related" (Q4-Q6) and "agency- related" (Q10-Q12) concerned ownership and agency indirectly (Zhang and Hommel, 2015). Scores from Q10–Q12 were reverse-coded, as the corresponding questions are phrased in terms of a loss of control over the tool. According to Kalckert and Ehrsson (2012), Kalckert and Ehrsson (2014), an average score needed to be higher than +1 to indicate the emergence of ownership and agency. In our virtual tool-use training as a motor sequential learning task, both the movement and its outcomes were closely tied to the participants' bodies, requiring judgments about embodied feelings of agency rather than external agency linked to the virtual tool-use. This design bridges the gap between studies of tool embodiment and explicit ownership and agency.

2.5 Analogue scale for measuring subjective control

After every set of 10 trials during both practice sessions, a virtual slider on a gray bar appeared (cf., Figure 3). The cube was not visible while participants operated the slider. Participants could move the slider from left to right on the gray bar to rate their subjective sense of control (extreme left = "no control at all", extreme right = "perfect control"). To create an intuitive input method, participants simply needed to move their right hand, and the slider immediately followed their hand movement.

Participants were instructed to indicate their subjective impression about how well they felt in control of the tool during the last set of trials by placing the slider at the relative position that best corresponded to their sense of control. Once they found this position, they just needed to keep the slider in place. After 10 s, the slider and the bar disappeared automatically, and the final response (i.e., the precise position of the white box) was recorded. The internal range of these values was between ±18.5 from the left to the right side of the slider bar. Technically, the minimum and maximum values (±18.5) denote the abstract internal size of the scale, which is scaled in the x-dimension of the physical table (ca. 37cm), which is also the limit of the movement range of the virtual tool. The participants were able to manipulate a seamless visual-analogue scale from left to right, and those numbers were entirely in the background, and only "No control at all" and "perfect control" were visible. Since participants reported only positively, thus, −18.5 can be considered 0% and +18.5 can be considered 100% on the scale. Therefore, to further use the values for statistical analyses, the scale was transformed from 0 − ±100% to have a relative change. The average scores of slider position, depending on the feedback presented during each session of virtual tool-use training, are further used for data analysis. Figure 2 illustrates slider position responses collected during each virtual tool-use training block with vision-only and visuo-tactile feedback.

FIGURE 2
Virtual slider.

2.6 Measure of task load

To measure subjective task load, the NASA Task Load Index (TLX) assessment (Hart and Staveland, 1988) was used after each training block with virtual tool use training. Participants rated six

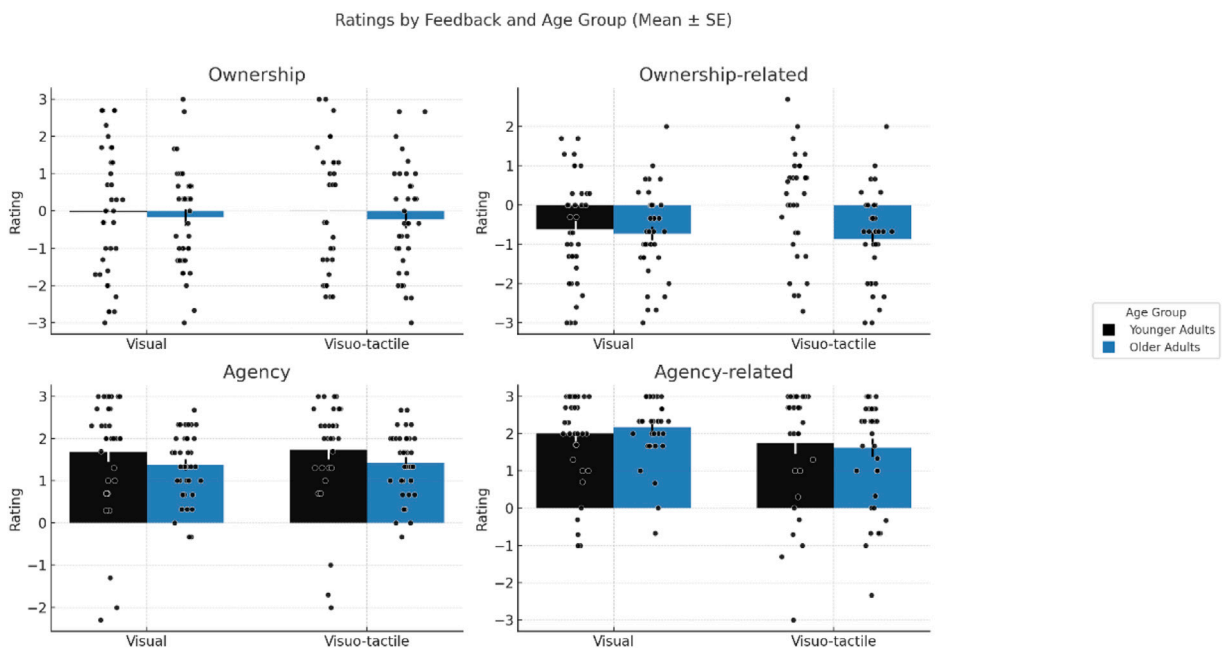

FIGURE 3
Ratings of Ownership, Ownership-Related, Agency, and Agency-Related experiences across feedback modalities and age groups. The top row presents Ownership and Ownership-Related responses; the bottom row shows Agency and Agency-Related responses. Data are grouped by Feedback type (Visual vs. Visuo-tactile) and split by age group (Younger Adults vs. Older Adults). Bars represent group means, with standard error of the mean (SE) indicated by error bars. Individual participant responses are overlaid as jittered points to illustrate variability within groups.

dimensions, including mental load, physical load, temporal load, effort, performance, and frustration on a 20-point scale, where 0 represented very low levels and 20 indicated very high levels. Following the recommendation of Galy et al. (2017), we used the scores from each dimension of the task load rather than the global score for further analysis in this study.

2.7 Data analysis and statistics

The dataset that was generated and (re)analysed during the current study will be made available on publication in an Open Science Framework repository on OSF.io. Inferential statistics were performed with R (R Core Team, 2024; R packages v4.1.1; RStudio v1.4.1717) and the Jamovi software environment (version 2.2.5.6.2; The Jamovi project, 2024), and plots were created by Python (version 3.12). Effects of task load on measures of ownership, agency, and sense of control, as well as timing performance during tool use, were analyzed using a general linear models (GLM) including age and feedback conditions as factors and in three-way interactions. Prior to analysis, outliers were removed based on two standard deviations.

3 Results

3.1 Sense of ownership and agency over the virtual tool

As already reported in Jahanian Najafabadi et al. (2023a), Jahanian Najafabadi et al. (2023b), according to the questionnaire data, both groups of young and older adults developed a sense of agency over the virtual tool measured after virtual tool use training with and without visuo-tactile feedback. For younger adults, the analysis of ownership and agency showed mean values of 0.0 ± 0.1 and −0.3 ± 0.1 for ownership and ownership-related, while agency and agency-related had mean values of 1.7 ± 0.1 and 1.8 ± 0.1, respectively (means and SE). This indicates that only the mean values for agency and agency-related exceeded the threshold of 1 proposed by Kalckert and Ehrsson (2012), Kalckert and Ehrsson (2014), whereas ownership and ownership-related did not. Figure 3 provides a breakdown of these results by feedback condition and test. For older adults, the analysis revealed mean values of −0.3 ± 0.07 and −0.8 ± 0.05 for ownership and ownership-related, while agency and agency-related had mean values of 1.4 ± 0.4 and 1.9 ± 0.6, respectively (means and SE; cf., Figure 3). Similar to younger adults, only the mean values for agency and agency-related surpassed the threshold, while ownership and ownership-related remained below this level.

3.2 The association between tool embodiment and task load

Building on the current findings, the slider scores were added, representing the subjective sense of control over virtual tools. Bivariate Pearson correlations were calculated between slider values (averaged from responses collected during virtual tool-use training) and ratings of ownership, ownership-related measures, agency, and agency-related measures, as assessed by the questionnaire. Additionally, the relationship between task load

FIGURE 4
Slider ratings across feedback modalities and age groups. Bars represent average ratings provided by participants in response to tool-use experiences under two conditions: Visual and Visuo-tactile feedback. Younger Adults and Older Adults are compared within each condition. Error bars reflect the standard error of the mean (SE), with a minimum display threshold applied for visibility. Individual participant ratings are overlaid as jittered points to illustrate distribution and variability within each group.

and the experience of ownership and agency within each age group was further investigated using bivariate Pearson correlation. The analysis further investigated the extent to which task load predicted ratings of ownership and agency, and whether feedback influenced this relationship. Figure 4 illustrates slider ratings across feedback modalities and age groups.

For younger adults, significant correlations were observed between sense of control values and ownership (r = 0.204; p < 0.001) as well as ownership-related ratings (r = 0.177; p < 0.001). In contrast, no significant correlation was found with agency (r = 0.29; p = 0.577), and a negative but non-significant correlation was noted with agency-related ratings (r = −0.086; p = 0.102). For older adults, sense of control values was significantly correlated with ownership (r = 0.25; p = 0.046), ownership-related ratings (r = 0.29; p = 0.017), and agency (r = 0.301; p = 0.015). However, no significant correlation was found for agency-related ratings (r = 0.035; p = 0.182).

Subsequent analyses examined whether task load predicted the experience of ownership and agency over the virtual tools. In younger adults, the results revealed a significant correlation between task load and ownership ratings, with mental load showing a positive correlation (r = 0.242, p = 0.04), performance load a negative correlation (r = −0.262, p = 0.03), and a negative marginally significant correlation with frustration (r = −0.22, p = 0.07). Additionally, physical load was negatively correlated with agency ratings (r = −0.26, p = 0.03). In older adults, the results revealed that only performance load was negatively marginally correlated with agency ratings (r = −0.215, p = 0.06), but not for other variables.

General Linear Models (GLM) were conducted with ownership or agency ratings as dependent variables, feedback condition as a factor, and task load as a covariate. For younger adults, the results revealed a marginally significant main effect of mental load (F (1, 64) = 3.62, p = 0.06), performance load (F (1, 64) = 7.25, p = 0.009), and frustration load (F (1, 64) = 3.14, p = 0.08). Additionally, a marginally significant interaction effect between performance load and visuo-tactile feedback condition was found (F (1, 64) = 3.62, p = 0.08) on ownership ratings. Moreover, a significant main effect of physical load was observed (F (1, 64) = 4.98, p = 0.029), which was associated with higher ratings of agency. For older adults, the results only revealed a marginally significant main effect of performance load (F (1, 70) = 3.27, p = 0.07) with higher agency ratings.

GLM was further fitted to the data using the sense of control scores as a dependent variable, feedback condition as a factor, and task load as a covariate. For younger adults, the results revealed a significant main effect of mental load (F (1, 52) = 4.68, p = 0.035), physical load (F (1, 52) = 7.67, p = 0.008), performance load (F (1, 52) = 7.25, p = 0.038), effort load (F (1, 52) = 8.14, p = 0.006), and frustration load (F (1, 52) = 5.69, p = 0.021). Additionally, a marginally significant interaction effect between performance load and visuo-tactile feedback condition was found (F (1, 52) = 5.41, p = 0.024) on sense of control responses. For older adults, the results revealed a significant main effect of effort load (F (1, 52) = 5.59, p = 0.022), and frustration load (F (1, 52) = 4.84, p = 0.032). Additionally, a marginally significant interaction effect between performance load and visuo-tactile feedback condition was found (F (1, 52) = 5.41, p = 0.024) on sense of control responses.

3.3 Task loads and their impact on tool embodiment and performance

An additional set of GLM analyses was conducted to examine age effects on Ownership and Agency ratings, entered as dependent variables in separate models. Task load components were included as covariates alongside Session and Age Group. For Ownership, results in younger adults showed significant effects of mental load (F(1,66) = 8.77, p = 0.004, η^2p = 0.117; R^2 = 0.178, adj. R^2 = 0.09), effort load (F(1,66) = 4.58, p = 0.036, η^2p = 0.070; R^2 = 0.116, adj. R^2 = 0.023), and temporal load (F(1,66) = 5.94, p = 0.017, η^2p = 0.08; R^2 = 0.182, adj. R^2 = 0.1). For Agency, analysis revealed a significant effect of physical load (F(1,66) = 5.07, p = 0.028, η^2p = 0.07; R^2 = 0.127, adj. R^2 = 0.035), independent of age group. This indicates that participants who reported higher physical task demands tended to experience reduced agency, whereas other task load components did not significantly predict Agency ratings. A GLM was conducted to test whether the subjective sense of ownership over the tool predicted faster task performance, measured as time reduction. The model included Age Group (Younger Adults, Older Adults) and Feedback (Visual, Visuo-haptic) as between-subjects' factors, Ownership ratings as a covariate, and all two-way and three-way interactions. The overall model was significant (F(7,130) = 2.80, p = 0.010, R^2 = 0.131, adj. R^2 = 0.084). A robust main effect of Age Group was observed (F(1,130) = 17.51, p < 0.001, η^2p = 0.12). Younger adults showed greater time reductions than Older Adults (Estimate = 3.14, SE = 0.75, t(130) = 4.18, p < 0.001). No main effect of Feedback was found (F(1,130) = 0.69, p = 0.409, η^2p = 0.005), and Ownership ratings did not predict performance (F(1,130) = 0.002, p = 0.965, η^2p ≈ 0). None of the two-way or

three-way interactions reached a significant level (all *ps* > 0.48). Post hoc comparisons further demonstrated that in younger adults in the Visual feedback condition significantly greater time reduction compared with older adults in the visual condition (Δ = −3.67, *SE* = 1.04, *t*(130) = −3.54, *p* = 0.003, Bonferroni-corrected), and also compared with older adults in the visuo-haptic feedback condition (Δ = 3.77, *SE* = 1.05, *t*(130) = 3.58, *p* = 0.003).

3.4 Age-dependent relationship between agency and tool-use performance

A GLM was further performed to examine whether subjective agency ratings predicted tool-use performance, measured as time reduction. The model included Age Group (Younger Adults, Older Adults) and Feedback (Visual, Visuo-haptic) as between-subjects' factors, Agency ratings as a covariate, and all two-way and three-way interactions. The overall model was significant ($F(7,130) = 3.46$, $p = 0.002$, $R^2 = 0.157$, adj. $R^2 = 0.111$). A strong main effect of Age Group was found ($F(1,130) = 16.34$, $p < 0.001$, $\eta^2p = 0.11$). Younger adults achieved greater time reductions than older adults (Estimate = 3.02, *SE* = 0.75, *t*(130) = 4.04, *p* < 0.001). Feedback did not significantly affect performance ($F(1,130) = 0.77$, $p = 0.382$, $\eta^2p = 0.006$). Agency ratings did not emerge as a significant predictor ($F(1,130) = 1.53$, $p = 0.219$, $\eta^2p = 0.01$). There was, however, a significant Age Group × Agency interaction ($F(1,130) = 3.95$, $p = 0.049$, $\eta^2p = 0.03$). Parameter estimates indicated that the relationship between agency ratings and performance differed across age groups, with a negative slope for older adults compared to younger adults (Estimate = −1.53, *SE* = 0.77, *t*(130) = −1.99, *p* = 0.049). No other interactions were significant (all *ps* > 0.48). Post hoc comparisons demonstrated that younger adults in the visual condition performed significantly better than older adults in the visual condition (Δ = −3.54, *SE* = 1.03, *t*(130) = −3.44, *p* = 0.005, Bonferroni-corrected), and also outperformed older adults in the visuo-tactile condition (Δ = 3.68, *SE* = 1.04, *t*(130) = 3.54, *p* = 0.003). No significant differences were observed between feedback conditions within the same age group.

GLM was further conducted with Age Group (Younger Adults, Older Adults) and Feedback (Visual, Visuo-tactile) entered as between-subjects' factors, Slider ratings (sense of control) included as a covariate, and Time Reduction (improvement relative to the 20-s maximum) as the dependent variable. Higher values reflect faster task completion. The analysis revealed a significant main effect of Age Group ($F(1,107) = 35.62$, $p < 0.001$, $\eta^2p = 0.25$). Younger adults achieved significantly greater time reductions than older adults (Estimate = 1.41, *SE* = 0.24, *t*(107) = 5.97, *p* < 0.001). No main effect of Feedback was observed ($F(1,107) = 0.13$, $p = 0.723$, $\eta^2p \approx 0$), indicating similar performance in the visual and visuo-tactile conditions (Estimate = −0.08, *SE* = 0.24). Ratings of sense of control showed a significant covariate effect ($F(1,107) = 8.93$, $p = 0.003$, $\eta^2p = 0.08$), with higher ratings predicting greater time reduction (Estimate = 0.017, *SE* = 0.006, *t*(107) = 2.99, *p* = 0.003). The interaction between Age Group and Feedback was also significant ($F(1,107) = 3.87$, $p = 0.052$, $\eta^2p = 0.04$), suggesting a possible difference in feedback effects between age groups. However, this did not reach conventional levels of significance. Bonferroni-corrected *post hoc* comparisons demonstrated that older adults' performance did not differ between visual and visuo-haptic feedback (Δ = −0.38, *p* = 1.00). Younger adults outperformed older adults in both conditions, with significant differences in visual (Δ = −1.87, *t*(107) = −5.71, *p* < 0.001) and visuo-tactile feedback (Δ = −1.33, *t*(107) = −3.91, *p* < 0.001). Within younger adults, performance did not differ significantly between feedback types (Δ = 0.55, *p* = 0.633, $R^2 = 0.335$, adj. $R^2 = 0.311$).

4 Discussion

To examine the effects of task load on the emergence of ownership, agency, and control over a virtual tool during training, we introduced a virtual analogue scale as a new instrument to complement the established questionnaires. In contrast to the questionnaires, this tool could be used directly during training. In addition, the analysis focused on whether perceived task load during virtual tool-use training affects the extent of tool embodiment. We further investigated how age, feedback modality, and subjective embodiment affect tool-use performance, as measured by time reduction during tool-use training. Both younger and older adults showed a significant correlation between slider values and ownership. However, a significant correlation between the slider and agency ratings was found only for older adults. This suggests that, for younger adults, the embedded slider may be capturing a different aspect of subjective experience compared to the agency measures from the questionnaire, which was presented after the training blocks were completed. While the slider reflects a more immediate sense of control, the questionnaire seems to measure a more abstract or generalized sense of agency. Additionally, the results show that age was the strongest predictor of tool-use performance, with younger adults consistently completing the task more quickly than older adults. Slider ratings also predicted faster performance, indicating that a greater sense of control facilitated tool-use efficiency. In contrast, feedback modality (visual vs. visuo-tactile) and ownership ratings had no effect, and their interactions were nonsignificant. Agency ratings alone did not predict performance, though the interaction of age × agency suggests that the role of agency may differ between younger and older participants.

4.1 The effect of task load on ownership, agency, and sense of control during virtual tool use training is age-dependent

Our findings reveal that task load affects ownership and agency as well as perceived control over the virtual tool, although the impact varies between younger and older adults. For younger adults, task loads, such as mental and performance load, seem to have a strong influence on their experiences of ownership and agency. Specifically, mental load was positively linked to ownership, suggesting that when participants were more mentally engaged in the task, they felt a stronger sense of ownership. In contrast, performance load had a negative relationship with ownership, suggesting that as the task became more complex, participants felt less ownership. This could likely be due to the additional cognitive effort needed to manage the

increasing loads. Frustration load, though only marginally significant, also appeared to reduce the feeling of ownership, with higher frustration slightly diminishing participants' sense of control over the task. This aligns with the idea that task difficulty and frustration can undermine one's sense of control over a virtual object or tool. When it comes to agency, physical load emerged as a key factor. Here, the more physical effort was required, the less control participants felt over the virtual tool. This suggests that there may be a trade-off between physical engagement and the perceived sense of agency. As physical effort increased, it may have either overloaded their cognitive resources or caused physical strain, which in turn reduced their sense of control. With respect to the virtual slider ratings of experienced control over the tool, the data showed significant effects of mental, physical, and performance loads on slider responses. These results suggest that as task loads increase, the immediate perception of control over the virtual tool decreases. The interaction between performance load and feedback type was also marginally significant, highlighting that ownership ratings are particularly sensitive to feedback when task loads are high.

In contrast to the young adults, the effects of task load on ownership and agency were weaker for older adults. The only significant predictor of a sense of agency was performance load, which showed a slight negative correlation. This indicates that older adults were less affected by task load in their perceived control over the virtual tool compared to younger adults. It's possible that older adults' sensorimotor systems are less sensitive to the loads of the task, making them less reactive to variations in task load. Additionally, the lack of significant correlations between task load and ownership in older adults suggests that their sense of ownership may be more stable (Jahanian Najafabadi et al., 2023b; Devlin and Wilson, 2010), less influenced by task load, and less susceptible to the task (Weser and Proffitt, 2021), possibly due to age-related differences in cognitive processing. We therefore suggest that older adults might use different mechanisms to compensate for the lack of necessary resources when performing motor tasks (e.g., Doumas et al., 2008; Ward et al., 2022; Goh et al., 2021). The effects of task load were less pronounced for the ratings of sense of control obtained during training, but the analysis still indicated that effort and frustration loads played a role in shaping these responses, similar to what was observed in the questionnaire data. While task load had a weaker impact on ownership and agency for older adults, the slider measure captured these subtle influences, suggesting that their experience is still sensitive to task load, even if less so than for younger adults.

Overall, our results support prior findings (Howard et al., 2016; Hon et al., 2013) indicating that a reduced sense of agency was associated with high effort load using explicit measures. These effects might also be related to the notion that agency itself is cognitively costly (Neszm´elyi and Pfister, 2024). It can be suggested that when cognitive resources are limited, the system's ability to predict sensory outcomes and the results of intentional actions is impaired, leading to a reduced sense of agency. In situations where the task load is higher due to mental or physical strain, there are fewer resources available to accurately track motor movements. As a result, the ability to attribute actions to oneself becomes disrupted (Howard et al., 2016). Therefore, the results from studies on cognitive processes and motor control in both age groups support the cognitive resource competition theory of a sense of agency (Huxhold et al., 2013; Lacour et al., 2008). This theory proposes that individuals with varying cognitive capacities, such as young and older adults, employ different strategies to avoid cognitive overload and perform tasks at their optimum level.

In line with this theory, our findings suggest that older adults may experience greater difficulty when task demands compete for limited cognitive and motor resources. One possible interpretation is that their sense of agency and ownership may be more fragile under high load (see Qu et al., 2021). In this regard, our slider task provided a particularly sensitive, real-time measure of agency and ownership, which may be especially suitable for older adults compared to retrospective questionnaires that require additional memory and cognitive processing resources, as well as motoric control to mark the response.

Looking forward, these insights point toward promising directions for training and rehabilitation. For example, future work could develop applications that help both younger and older adults to practice monitoring and strengthening their sense of agency in demanding motor tasks. Such "embodiment and agency sensitivity trainings" could use real-time measures (e.g., the slider) combined with virtual tool-use tasks and personalized feedback to improve sensitivity to changes in both dimensions. Importantly, this would allow us to test whether older adults benefit from such interventions.

Analogies from racket sports (e.g., table tennis, tennis) highlight the broader principle: Expert players must continuously adapt to subtle changes in tools (e.g., racket surfaces) and environmental conditions (e.g., spin of the ball). In comparison, older adults may be regarded as experienced tool users (Weser and Proffitt, 2021), who may have relatively fixed expectations and established preferences. They may thus retain a relatively stable sense of ownership across a lifetime of practice with a certain range of tools. Conversely, their flexibility to adapt to unfamiliar tools under high task load may be reduced. Training approaches could therefore be designed to both harness this stability and provide structured exposure to varying levels of difficulty, gradually adapting cognitive and motor demands. Similarly, samples of older and younger expert racket sport players might provide new insights into the role of embodiment sensitivity.

Finally, the familiarity of participants with immersive technologies such as VR/AR should also be considered. Older adults may benefit from graduated exposure, starting with simpler, low-load interactions before progressing to more demanding tasks that challenge tactile and visuospatial processing. Future work could therefore explore how adaptive training systems can calibrate task difficulty in real time, ensuring that resource allocation remains manageable while still fostering plasticity.

Altogether, more studies are needed to precisely focus on the effects of task load and its influence on the emergence of ownership and a sense of agency during tool use training. Future studies could examine variability in implicit, embedded, and explicit measurements, as well as task difficulty and age differences, to better understand how these factors may explain differences in tool use performance, ownership, and agency. Moreover, we suggest including implicit measurements of ownership and agency in association with explicit measures during tool-use tasks. Additionally, further studies are needed to investigate neural mechanisms underlying these effects, considering age-

dependent neural processes as reported in our prior experimental research comparing old and younger adults during the same virtual tool-use training, which suggested that older adults might rely on different neural and cognitive mechanisms when performing a motor task due to their age-related sensorimotor declines (Jahanian Najafabadi et al., 2023a).

4.2 A higher sense of control during tool use affects timing performance

Interestingly, our analyses revealed that age was the strongest factor influencing tool-use performance, with younger adults consistently completing tasks more efficiently than older adults. A higher subjective sense of control measured during tool use was also associated with faster task completion, suggesting that the experience of agency over the tool may support timing performance. However, agency ratings measured after tool use training alone did not reliably predict timing performance across participants. Here, an age-dependent relationship emerged, with younger adults showing a positive link between agency and timing performance, while in older adults, higher agency ratings did not translate into better outcomes and in fact tended toward the opposite pattern. Feedback modality (visual vs. visuo-haptic) had no significant influence on performance in either age group. Overall, these results indicate that while a strong sense of control can facilitate efficient tool use, its role may differ with age such that older adults appear less able to translate perceived agency into measurable improvements in performance. These findings suggest that older adults may be less able to translate perceived agency into measurable improvements in performance, potentially reflecting age-related declines in cognitive, sensory, or motor integration processes (Cioffi et al., 2017; Weser and Proffitt, 2021; Jahanian Najafabadi et al., 2023b). This interpretation is consistent with evidence that the sense of agency and ownership, although closely linked, are supported by partially distinct cognitive mechanisms, creating a double dissociation between them (Kalckert and Ehrsson, 2012).

Importantly, the current results further indicate that timing performance during tool use may be more sensitive to agency assessed in real time during task execution, rather than to retrospective ratings collected after training, which are more vulnerable to memory distortions (Nicolaï et al., 2024). Moreover, previous work suggests that older adults may require more time to complete motor tasks and may not reach the same level of accuracy as younger adults, even when augmented feedback is provided (for review; Voelcker-Rehage, 2008). The study by Nataraj et al. (2020) further showed that a stronger sense of agency, measured implicitly through intentional binding, is closely linked to better motor performance across different control conditions. This supports the broader view that feeling in control helps people integrate more smoothly with tools or devices, which can enhance both learning and functional outcomes. Our findings partly fit this picture: younger adults who reported a stronger sense of control during tool use performed more efficiently. However, an important age-related difference emerged. Unlike younger adults, older adults did not show the same benefit from higher agency, and in some cases, greater reported agency was even linked to reduced performance. This suggests that the positive link between agency and performance described by Nataraj et al. (2020) may not apply equally across age groups. One explanation could be that implicit measures of agency, such as intentional binding, capture automatic and relatively stable aspects of agency that may be preserved in older age, whereas explicit self-reports such as the questionnaires used in our study, are more vulnerable to cognitive decline, sensory noise, or memory distortions. Another possibility is that older adults experience a mismatch between how much control they feel they have and their actual motor outcomes, due to age-related changes in sensorimotor integration (Seidler et al., 2009; Voelcker-Rehage, 2008).

Despite these differences, both studies point to agency as a central factor for motor learning, rehabilitation, and user–device interaction. Our results highlight that the role of agency may depend on both age and the way it is measured. Following the framework of Nataraj et al. (2020), future work could test whether implicit and embedded measures of agency provide a more reliable predictor of performance measured by, e.g., trial timing in older adults, and whether VR-based approaches can be used to tailor control strategies that support both the subjective experience of agency and functional motor outcomes.

5 Conclusion and future directions

The present study shows that age is a central factor in tool-use performance, with younger adults completing the task more efficiently than older adults. In addition to age, participants' immediate sense of control, as reflected in slider ratings, predicted faster performance. In contrast, feedback modality and ownership ratings did not. Agency ratings did not independently predict timing, although their relationship with performance differed by age group. These findings indicate that the dimensions of embodiment contribute differently to tool-use efficiency and highlight the value of combining broad, reflective questionnaire measures with sensitive trial-level slider ratings. Together, this approach offers a more comprehensive account of how control, ownership, and agency shape virtual tool use and provides a basis for future work on the sensory and motor mechanisms that underlie embodied interaction.

Our experimental design can be refined and expanded to explore how various types of predictions, such as sensory and motor predictions, interact and computationally integrate to produce a cohesive sense of agency and ownership over physical and virtual tools. For instance, future studies could investigate the relative weighting of these predictions in different contexts and further examine how conflicting sensory signals are resolved to maintain a stable perception of control in the context of tool embodiment. Additionally, this approach could be used to explore individual differences in the integration process, such as how factors like neurological conditions influence the balance of these predictions in shaping the sense of agency and ownership. By addressing these questions, we can gain a deeper understanding of the underlying mechanisms that contribute to the seamless feeling of control over our actions and their outcomes. The new slider measures, in our view, complement the traditional questionnaire measures. Together, both offered a more comprehensive understanding and insight into how task load shapes ownership and agency over virtual tools than

in previous studies. The questionnaire offers a broader, reflective view of these experiences, while the slider provides a more immediate and nuanced understanding of how participants perceive control over virtual tools after every set of training trial.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study was approved by the Ethics Committee of the University of Bremen (06/03/2018). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

AJ-N: Investigation, Writing – original draft, Visualization, Formal Analysis, Validation, Conceptualization, Project administration, Writing – review and editing, Data curation, Methodology. DK: Conceptualization, Funding acquisition, Writing – review and editing, Resources, Project administration, Methodology, Software. FP: Conceptualization, Resources, Software, Funding acquisition, Project administration, Writing – review and editing. BG: Resources, Project administration, Conceptualization, Writing – review and editing, Funding acquisition.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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