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Embodying an elderly virtual avatar impairs metacontrol persistence but not flexibility in college students

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ABSTRACT

The enfacement illusion occurs when synchronous multisensory correlations between a viewed face and one's own face lead to the perception of illusory ownership, in which participants incorporate the viewed face's physical and social features into one's body representation. In this study, we examined whether young participants exposed to synchronous visuo-motor correlations with a virtual elderly face would perceive ownership of that face, exhibit subjective aging and executive function decline resembling physiological aging. Questionnaire and subjective age ratings confirmed that illusory ownership and agency were successfully induced for same-gender virtual elderly faces. Interestingly, however, synchronous multisensory correlations impaired performance in a cognitive-control task calling for metacontrol persistence (a Simon task), but not in cognitive-control tasks calling for flexibility (N-back task and task switching). These findings align with prior evidence that synchrony with another face/body facilitates the integration of external features into self-representation, and that this affects cognitive control; but they also demonstrate that the control functions being affected are specific to the type of embodiment.

1. Introduction

Self-body representation refers to how we represent our body in the brain, with the sense of ownership, the feeling that a body part belongs to oneself, serving as a core component (Gallagher, 2000). When investigating ownership, experimental paradigms often make use of various kinds of illusions, including the rubber hand illusion (RHI), the enfacement illusion, and full body illusions (Blanke & Metzinger, 2009; Lenggenhager, Tadi, Metzinger, & Blanke, 2007). These illusions demonstrate that and how multisensory integration (visual, tactile, motor and proprioceptive, etc.) can induce a coherent sense of body ownership over an external body or body part (Botvinick & Cohen, 1998; Blanke & Metzinger, 2009).

In RHI, synchronized stroking of a visible rubber hand and a hidden real hand creates illusory ownership (Ramachandran, 1998). Similarly, enfacement and body illusions elicit self-identification of participants with observed face and body through matched visuotactile stimulation (Tsakiris, 2008). Participants not only perceive the other face/body as their own, but also blur the physical and social boundaries between representations of self and other. These illusions demonstrate the malleability of facial/identity recognition and self-representation.

Virtual reality (VR) extends these paradigms by enabling dynamic embodiment through motion tracking and avatar customization. Synchronized multisensory correlations in VR induce robust ownership illusions regarding virtual bodies or body parts, especially with

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respect to the enfacement and body illusion. To induce such illusions, participants wear data gloves, head mounted displays, and body motion trackers, so that they can move their real body or body part and see the virtual face moving synchronously or asynchronously, so that much more multisensory information is involved than in more static experimental paradigms.

Importantly, the virtual avatar's physical and social characteristics (face, body, age, expression, gender and race, etc) can be systematically manipulated easily (Ma et al., 2016), which allows studying how people are influenced by the kind of embodiment that they experience. Typical results showed that, with ownership illusion on the virtual body/face, participants' behavior, mood and attitude, shifted away from their actual self and/or towards that of the embodied virtual body/face (Pyasik, Ciorli, & Pia, 2022; Maister, Slater, Sanchez-Vives, & Tsakiris, 2015). For example, the enfacement illusion has been shown to affect perceived interpersonal similarity, social attitudes of participants, and self-other integration between one's own body and the virtual body representations (Paladino, Mazzurega, Pavani, & Schubert, 2010).

Researchers found that illusory ownership can impact implicit attitudes. For example, inducing the ownership illusion over a black rubber hand or a black body in white participants was found to reduce their implicit racial bias towards black people (Maister et al., 2015; Peck et al., 2013), and these effects can persist for at least one week (Banakou et al., 2016). Along the same lines, embodying a virtual opposite-gendered avatar made participants perceive themselves as being more opposite-gendered (Tacikowski, Fust, & Ehrsson, 2020), and reduce their gender-science stereotypes (Zhang, Hommel, & Ma, 2021).

Body ownership illusions can also induce behavioral changes. For example, if adults watch themselves in a virtual mirror that presents them in a child's body which they can control by means of their own movements, they begin overestimating the size of viewed virtual objects (Banakou, Groten, & Slater, 2013). Also in one experiment, where the embodied virtual body was Sigmund Freud, participants demonstrated better mental consulting results (Osimo et al., 2015). Ownership of a virtual smiling face enhanced participants' mood ratings and performance on an emotion-sensitive creativity task (Ma et al., 2016), and embodying an ape's face induce significant reductions in the participants' fluid intelligence scores (Ma et al., 2019).

Of particular importance for our present study, when participants embodied a virtual Albert Einstein, with an old face and gray hair, their performance on the London Tower task improved, and age biases decreased (Domna et al., 2018). Some other previous studies have shown direct evidence on the behavioral effects of virtual aging. These findings suggest that "virtual aging" experiences can significantly induce the "Proteus Effect", where people's cognition, attitudes, and behaviors assimilate to their virtual identity. For example, the embodied perspective-taking of young participants can effectively reduce negative stereotyping on the elderly (Yee & Bailenson, 2006). Interacting with a virtual, aged future self can enhance "future self-continuity", and significantly increase saving behavior (Hershfield et al., 2011). After embodying a slower-moving elderly avatar, participants' walking speed in real-world decreases (Reinhard, Shah, Faust-Christmann, & Lachmann, 2020); and their motor imagery processes become slower (Beaudoin et al., 2020). Also, researchers found that, participants embodying older avatars showed declines in memory and physical performance (Vahle & Tomasik, 2022a), and lower preference for information seeking in social motivation (Vahle & Tomasik, 2022b).

Theoretical frameworks underlying body illusion studies are provided by embodied-cognition approaches and the theory of event coding (TEC). TEC (Hommel, 2004; 2009) proposes that cognitive systems represent perceived and self-generated events through an integrated feature-binding network, which does not distinguish between self-related and external events. The integration or discrimination of two events depends on their spatiotemporal synchrony, among other factors. When two events contain more overlapping features, people tend to confuse the two event representations, which in turn reduces discrimination between the two. That is, when participants experienced a virtual avatar from a first person perspective (Maselli & Slater, 2013), and if they can freely control its movements, the match of multisensory correlations between visual and interoceptive cues increases the feature overlap, so that participants may confuse the body representations of themselves and of the virtual avatar. To the degree that they do, they may be tempted to incorporate physical and social characteristics of the virtual avatar into their self-representation. Embodied cognition theory posits an intrinsic connection between cognition, sensation, and the physical body. Cognition emerges from the dynamic interaction of the brain, environment, and body, and eventually shaping individual behavior. Thus, with virtual ownership illusion paradigms, according to TEC, matched multisensory correlations make participants to feel that "I am the virtual avatar; the avatar body/face belongs to me; some features of the virtual avatar body are mine"; and according to embodied cognition, these physical and social implications associated with the virtual body influence people' behavior, attitude and mood.

Based on these theoretical considerations, in the present study, we assumed that when young participants experience synchronous multisensory correlations with an elderly virtual person in a VR environment, they may obtain a sense of ownership illusion towards the virtual elderly body. If so, they would feel that this virtual elderly body belongs to them and then experience subjective aging ("I am becoming old now") as a consequence. Accordingly, they may also show specific behavioral performance changes, similar to cognitive aging.

Cognitive aging refers to the progressive decline in cognitive abilities following physiological aging, primarily resulting from structural alterations of the brain (Glisky, 2007; Harada, Love, & Triebel, 2013). Especially, the prefrontal cortex is thinning, and its capacity to support executive functions is diminished with physiological aging (Dempster, 1992). Of particular interest for our present study, cognitive aging impairs executive functions, including the ability to exclude irrelevant information from information processing, to update working memory in the presence of new information, and to switch between different tasks (Li, Hämmerer, Müller, Hommel & Lindenberger, 2009; Li et al., 2004; Salthouse, 1996; Uylings & Brabander, 2002). Thus, we were interested in the impact of the ownership illusion on performance on executive function tasks, hypothesizing that embodying an elderly person may lead to similar impairments in executive control functions than actual physiological aging would do.

In this study, we considered three tasks tapping into executive control. Traditionally, executive functions, also termed as executive control or cognitive control, are taken to refer to a complex set of higher-order processes that operate in a top-down manner, requiring focused attention and, perhaps, conscious engagement (Miller & Cohen, 2001). The operations of executive functions are thought to

orchestrate internal and external actions, including planning, problem-solving, and sustained goal-directed behavior, primarily mediated by the prefrontal cortex (Alvarez & Emory, 2006; Diamond, 2013). More recently, however, it has been argued that this strong top-down approach to executive functions/cognitive control covers only one side of the control coin. While concentration, exclusion of seemingly irrelevant information, persistence of current goals, shielding of working memory and similar processes might indeed be useful under many circumstances; other conditions call for the exact opposite, namely, for opening up to alternative informational cues, readiness to change one's goals, the inclusion of seemingly irrelevant information into action planning and working memory—as for instance under conditions that require new ideas, alternative actions, or when current goals are simply dysfunctional (e.g., Goschke, 2000). Accordingly, researchers have suggested more comprehensive control concepts, which assumes the need to constantly regulate control between the poles of extreme persistence, which would represent the traditional control concept; and extreme flexibility (Cools & d'Esposito, 2009; Dreisbach & Goschke, 2004; Durstewitz & Seamans, 2008; Hommel & Colzato, 2017; Hommel & Wiers, 2017).

This more comprehensive approach (coined a *metacontrol* approach by Hommel & Colzato, 2017) fits well with approaches that have distinguish between different kinds of control functions, like selective attention, focused concentration, planning, inhibition, and cognitive flexibility (Hall et al., 2008; Hofmann et al., 2012), and psychometric approaches that separated distinct subcomponents of control: inhibitory control, updating and shifting (Miyake & Friedman, 2012). Even though there is evidence that cognitive aging might affect performance in various kinds of cognitive-control tasks (Cepeda, Kramer, & Sather, 2001; Glisky, 2007; Hasher et al., 2008; Raz, 2000), we were interested to test whether the embodiment of an virtual elderly avatar would affect all control functions alike, as the traditional approach to cognitive control would suggest; or whether persistence-heavy and flexibility-heavy tasks would be affected differently, as the metacontrol approach implies. Accordingly, we used one cognitive-control task that is calling for cognitive persistence (i.e., selection of relevant and exclusion of task-irrelevant information) in Experiment 1 and two cognitive-control tasks that are calling for cognitive flexibility (i.e., intake of novel information and switching to a new task) in Experiments 2 and 3.

We also considered subjective aging in the present study. Subjective age, which reflects personal awareness and perception of one's physiological aging process, serves as a key indicator of physiological/mental health status and brain age in the elderly (Galambos et al., 2005). Importantly, subjective age usually diverges from physiological age. Meta-analytic findings indicate that the subjective perception of "feeling younger" significantly and positively predicts cognitive control performance in older adults (Stephan et al., 2014). Those who perceive themselves as younger typically demonstrate better physiological health, memory performance, and lower mortality risk (Stephan, Chalabaev, Kotter-Grühn, & Jaconelli, 2013). Importantly, subjective age can be influenced by various factors, such as life experiences, physiological health status, age bias, and also value orientations (Kotter-Grühn et al., 2015; Stephan et al., 2012). Researchers have demonstrated that interventions which redirect attention and provide positive feedback, such as praising older adults for outperforming peers, can effectively reduce subjective age. Along the same lines, reducing subjective age can enhance physical performance, as evidenced by improved scores on grip strength tests (Stephan et al., 2013).

Overall, in this study, we ran three experiments to investigate: the effect of embodying an elderly virtual avatar on young participants, the role of subjective age, and performance in three executive cognitive-control tasks, one calling for metacontrol persistence and to others calling for metacontrol flexibility.

2. Experiment 1. Simon task

The traditional approach to cognitive control focuses on control functions that subserve the ability to suppress internal/external distractions, ignore irrelevant information, and maintain focus on target stimuli—often referred to as inhibitory control (Miyake & Friedman, 2012). As a core executive function component, it encompasses attentional regulation, interference suppression, and self-discipline (Diamond, 2013). In Experiment 1, we examined whether the embodiment of an elderly virtual avatar increases college students' subjective age and impairs their inhibitory control performance, which was assessed by means of the Simon task (for overviews, see Simon, Cespón, Hommel, Korsch, & Galashan, 2020; Hommel, 2011; Colzato et al., 2014). In the Simon task, faster reactions occur when stimulus and response locations spatially correspond (vs. incongruent positions) – known as the Spatial Simon Effect (Lu & Proctor, 1995; Proctor & Vu, 2002). Previous research on cognitive aging suggests that, older adults show reduced inhibitory capacity, are susceptible to interference from irrelevant stimuli (Castel et al., 2007), which would predict increase in reaction times and Simon effect in elderly populations (Craik, Luo, & Sakuta, 2010).

Our experimental hypothesis was thus as follows: compared to asynchronous conditions, in synchronous conditions participants should show higher scores of illusory ownership towards the avatar; increased subjective age; lower accuracy and longer reaction time in the Simon task, and an increased Simon effect.

2.1. Method

2.1.1. Participants

Sample size was determined by conducting a priori power analysis with G*Power (Faul et al., 2007), specifying a medium effect size ($f = 0.25$), a power ($1–\beta$) of 0.8, producing a required sample size of at least 24. Informed consents were obtained from all participants included in this study.

The participants were all from one university from China. Sixty college students (39 females and 21 males) were recruited through online announcements. The average age was 20.73 years old, with a standard deviation (SD) of 1.22 and an age range of 18–23 years old. All subjects have normal vision or corrected vision and are able to wear helmets to participate in VR experiments normally. No

participant had previous experience with the experiment. After the experiment, each participant could receive a certain amount of money as compensation.

2.1.2. Virtual reality equipment

The VR equipment included an HTC head mounted display (HMD) and HTC vive controllers, run under the VR software Vizard. Male and female virtual 3D face models were generated using Facegen software, with average Asian male and female faces (Ma, Sellaro, Lippelt, & Hommel, 2016). The age of the faces were set to 60 years old in Facegen, see Fig. 1. We imported the generated faces into the Vizard software. Thus, male and female participants were presented with gender-matched elderly avatars.

As shown in the Figs. 2 and 3 below, when the scripts were run, participants wore the HMD, and entered the VR room. We put a virtual mirror in front of the participants, which allowed participants to see the reflection, just like when they were looking themselves through the mirror, while in the mirror participants saw the virtual faces, but not their real faces.

2.1.3. Embodiment questionnaire

The ownership questionnaire consisted of 12 questions (Sforza, Bufalari, Haggard, & Aglioti, 2010; Tajadura-Jiménez et al., 2012; Ma et al., 2016), in which Q1-Q4 measured ownership illusion directly, Q5-Q6 were control questions for ownership, Q8-10 measured sense of agency, and Q7 and Q11-12 were control questions for agency (Tajadura-Jiménez et al., 2012; Ma et al., 2016). Participants needed to respond by a score using the Likert 7-point (1–7) scale, ranging from 1 for “strongly disagree” to 7 for “strongly agree”. The questions were:

Q1: I felt like the face on the screen was my own face.
Q2: It seemed that I was looking in the mirror.
Q3: I felt the movement and touch of this face in the mirror in front of me.
Q4: I felt like the touch on my face is caused by the ball hitting the face in the mirror.
Q5: It seemed like the face in the mirror had started to resemble my own face.
Q6: It seemed like my own face had started to resemble the face in the mirror.
Q7: It seems that my movement was caused by the face in the mirror.
Q8: The actions I see in the mirror seemed to be my own actions.
Q9: The face on the screen moved as I wanted, as if obeying my will.
Q10: When I move my face, I expect the face in the mirror to move the same.
Q11: It seemed like I had lost control over my own face.
Q12: It seemed that the face in the mirror has its own will.

We also asked participants to rate the subjective relationship familiarity and similarity between participants themselves and the seen virtual avatar, using the inclusion of others in the self (IOS) scale (Aron et al., 1992), through indicating which degree of overlap between participants’ own circle “You” and the virtual avatar face circle “X”.

2.1.4. Subjective age

The subjective age judgment was recorded twice, before and after the VR experience separately. Participants were instructed to subjectively assess how old they were based on their feelings in the current moment, and then mark a point on a line in the VR environment with the HTC vive controller. They could adjust it if needed, and then click the below OK button with the controller. The left and right endpoints of the line represented 0 and 120 years old. We did not ask participants to verbally report a number for the subjective age, in order to prevent participants from too much relying on their real age and initial reported subjective age (Hughes et al., 2013).

Fig. 1. The female (left panel) and male (right panel) virtual elderly face.

Fig. 2. Experimental setup, the participants wore the virtual reality hmd.

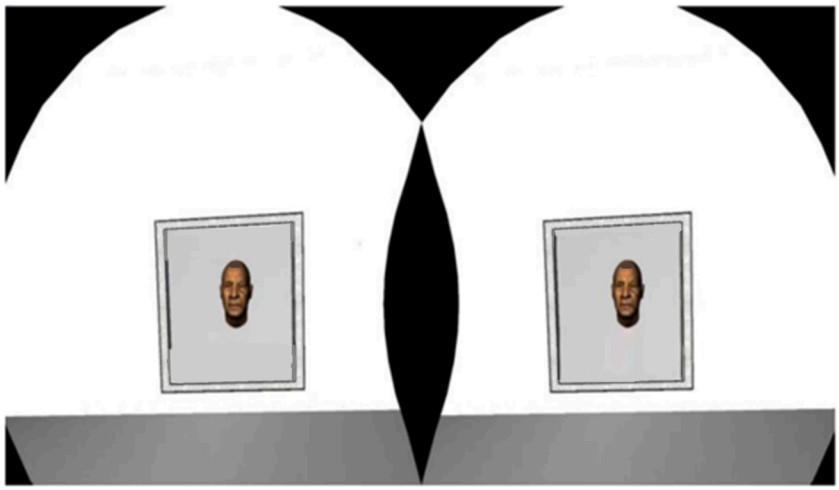

Fig. 3. The VR mirror and the virtual elderly face in the HMD.

2.1.5. Simon task

In each trial of the Simon task, a small black square was shown for 1000 ms in the center as fixation point, followed by a green or blue circle on the left or right side with equal probability. The task of the participants was to discriminate the color of the circle by pressing the "p" or "q" keys as quickly and as accurately as possible, while ignoring the location of the stimulus. Half of the participants pressed the "p" key in response to green color and the "q" key in response to blue color; the other half of the participants received the opposite mapping. The stimulus was presented for 1500 ms or until the participants pressed the button, and then the fixation point was presented for 1000 ms.

The task consisted of four blocks of 50 randomly ordered trials, where the first 5 trials of each block were practice trials and the remainder trials were experimental trials. In half of the trials, stimulus and response positions corresponded, the congruent trials; and in the other half, stimulus and response positions did not correspond, the incongruent trials. Participants could take a rest between blocks. Feedback about reaction time and accuracy was presented in the practice trials, but not in the experimental trials.

2.1.6. Experimental design

The experiment used a three-factorial within-participants design. One factor was synchrony (synchronous vs. asynchronous) between the movements of participants' real and virtual avatar faces, the second was stimulus–response congruency (congruent vs. incongruent), and the third was time (pre vs. post VR experience). Questionnaire results were analyzed as a function of synchrony; subjective age as a function of synchrony and time; and performance on the Simon task as a function of synchrony and stimulus–response congruency. The dependent variables included the scores of ownership questionnaire and IOS scale, subjective age judgement, and reaction time and accuracy in the Simon task.

2.1.7. Procedure

After arriving at the laboratory, participants sat down on a chair and adjusted to the situation. Then the experimenter instructed

participants how to use the HTC vive controller and helped them to put on HMD.

After that two synchrony (synchronous or asynchronous) conditions of the virtual experience started one by one. Each condition consisted five phases. First, participants made pre-experience subjective age judgments. Then the age line disappeared and a virtual avatar face (with the same gender as the participant) and the mirror appeared in the virtual room. Second, the visuo-motor correlation phase started, participants could freely move or rotate their real face and watch the virtual avatar face move. In synchronous conditions, the virtual avatar face moved the same way as the real face in real time; while in asynchronous conditions, the movement of the virtual avatar face was pre-scripted and totally unrelated to real face movements (asynchronous). This phase lasted for 90 s. Third, the visuo-tactile stimulation phase started, participants were asked to sit still and watch a virtual ball touching the avatar face in the mirror, in the meanwhile he/she could feel the touch on real face. The experimenter held a HTC vive controller and controlled the action of the ball. In synchronous conditions, the action of the virtual ball was the same, thus participants felt the touch when they saw the ball touching the virtual avatar face in the same position. In asynchronous conditions, the action of the ball was 3 s delayed, thus the seen and felt touch were asynchronous. This phase also lasted 90 s. Fourth, the virtual avatar face and mirror disappeared, and the age line appeared again, participants were to report their post-experience subjective age. Then participants finished the questionnaire which appeared in the virtual room on a virtual screen, by reporting the scores to experimenter. Fifth, after taking off the HMD, participants were asked to finish the Simon task.

There was a 5-minute break between the two conditions. During the virtual experience, participants were not informed of the degree of synchrony between their real face and the virtual avatar face. The order of synchronous and asynchronous conditions was counterbalanced between participants.

2.2. Results

We analyzed the scores of ownership questionnaire and IOS scale, also pre- and post-experience subjective age, and calculated the accuracy and reaction time in Simon task for each participant.

2.2.1. Embodiment questionnaire

Paired t-tests showed that, except for question Q7, $p = 0.115$, the synchrony effect was significant for ownership and agency items, $t(59) >= 2.64$, $p <= 0.011$, $d >= 0.34$. Except for question Q11, Q12, and agency control, scores were higher under synchronous than asynchronous conditions. Fig. 4 and Table 1 show the participants' ratings of the ownership and agency questionnaire under both synchrony conditions.

T-tests of the IOS data showed a significant synchrony effect, $t(59) = 9.566$, $p < 0.001$, $d = 1.24$, $BF10 > 100$, indicating that the score was significantly higher after synchronous conditions ($M = 4.02$, $SE = 0.17$) than after asynchronous conditions ($M = 2.50$, $SE = 0.14$).

2.2.2. Subjective age

The ANOVA showed no significant main effects of synchrony, $p = 0.094$, indicating that the subjective age was comparable under synchronous conditions ($M = 26.37$, $SE = 0.90$) than under asynchronous conditions ($M = 25.39$, $SE = 0.86$); and of time, $F(1,59) = 26.11$, $p < 0.001$, $p\eta^2 = 0.31$, $BF10 > 100$, indicating that the subjective age was higher after the virtual experience ($M = 28.34$, $SE = 1.10$) than before ($M = 23.43$, $SE = 0.81$). The interaction was also significant, $F(1,59) = 13.17$, $p = 0.001$, $p\eta^2 = 0.18$, $BF10 = 55$. Two-tailed paired t-tests found that subjective age was significantly higher for post-experience than for pre-experience, both in synchronous, $t(59) = 6.31$, $p < 0.001$, $d = 0.81$; and asynchronous conditions, $t(59) = 3.04$, $p = 0.004$, $d = 0.39$, $BF10s > 100$. In the pre-experience condition, subjective age showed no effect of synchrony, $p = 0.271$; while for post-experience, subjective age was

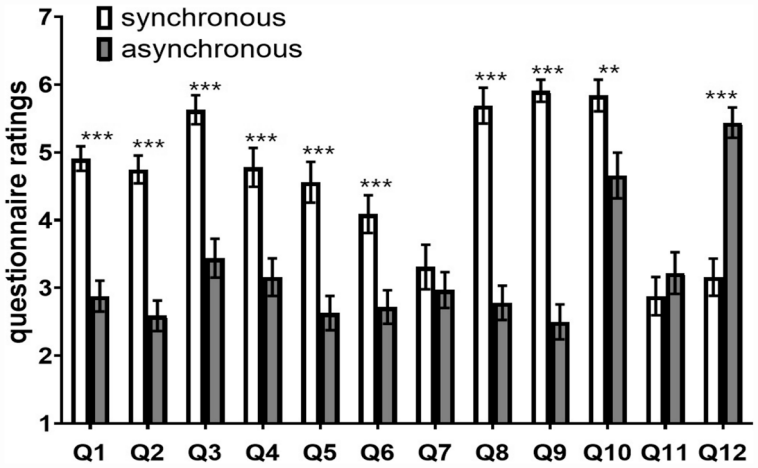

Fig. 4. The Embodiment questionnaire results, error bar represents standard error.

Table 1
The embodiment questionnaire and agency results, the mean and SE (in blanket) values.

	Ownership (Q1-4)	Ownership control (Q5-Q6)	Agency (Q8-10)	Agency control (Q7, Q11-Q12)
synchronous	4.46(0.16)	3.61(0.19)	5.51(0.12)	3.05(0.15)
asynchronous	3.00(0.17)	2.97(0.17)	3.57(0.19)	3.45(0.15)

significantly higher for synchrony than for asynchrony, $t(59) = 3.05$, $p = 0.003$, $d = 0.39$, $BF10 = 8.91$. See Table 2.

2.2.3. Simon task

Mean correct reaction times (RTs) and percentage of accuracy (%) were submitted to separate repeated-measures ANOVAs, with congruency between the stimuli and response positions in present trial and synchrony as within-subjects factors.

The ANOVA of RTs yielded a significant main effect of congruency, $F(1,59) = 73.50$, $p < 0.001$, $p\eta^2 = 0.56$, $BF10 > 100$, indicating that RTs were faster in congruent trials ($M = 467.15$, $SE = 9.77$) than in incongruent trials ($M = 490.05$, $SE = 9.30$)—a Simon effect of 23 ms. While the main effect of synchrony was not significant, $p = 0.389$; the interaction between synchrony and congruency was, $F(1, 59) = 9.03$, $p = 0.004$, $p\eta^2 = 0.13$, $BF10 = 7.81$. Two-tailed paired t-tests revealed a significant congruency effect for both the synchronous condition, $t(59) = 9.46$, $p < 0.001$, $d = 1.23$, and the asynchronous condition, $t(59) = 6.76$, $p < 0.001$, $d = 0.87$, $BF10s > 100$. But the size of the congruency effect was significantly larger for the synchronous than for the asynchronous conditions, $t(59) = 3.01$, $p = 0.004$, $d = 0.39$, $BF10 = 7.99$. In other words, synchrony boosted the Simon effect.

The ANOVA of Accuracy yielded a main effect of congruency, $F(1,59) = 15.76$, $p < 0.001$, $p\eta^2 = 0.21$, $BF10 > 100$, indicating that accuracy was higher for congruent trials ($M = 97.27$, $SE = 0.39$) than for incongruent trials ($M = 95.34$, $SE = .54$). The effects of synchrony and the interaction were not significant, $ps > 0.16$. See Table 3 and Fig. 5.

2.2.4. Correlation analysis and sensitivity power analysis

We computed the Simon effect using the subtraction between inconsistent RT and consistent RT; and also computed the subjective age changes using the subtraction between post and pre results. We then analyzed the correlational relationships between ownership, agency ratings, Simon effect, also subjective age changes, separately for synchronous and asynchronous conditions. Results showed that, when synchronous, significant correlations were found between ownership and agency, with $r = 0.594$, $p < 0.001$, consistent with previous findings (Ma & Hommel, 2015). When asynchronous, significant correlations were found between ownership and agency, with $r = 0.636$, $p < 0.001$; also between ownership and subjective age changes, with $r = 0.318$, $p = 0.007$, suggesting that the more college participants enfaced with the virtual elderly face, the older they felt. No other significant correlation was found, $ps > 0.07$.

We also conducted a sensitivity power analysis, for the observed effect sizes (the significant interaction effect, $p\eta^2 = 0.13$), power = 0.8, alpha = 0.05, the minimum required sample size is 55, suggesting that the current sample size is adequate for us to find the significant influence of synchrony on the Simon effect.

2.3. Discussion

The significant synchrony main effects for the Embodiment questionnaire and the subjective age results indicate that the intended manipulation of self-perceived age worked as expected: participants felt older after experiencing spatial–temporal synchrony with an elderly virtual face. In other words, controlling a human-like avatar induce the adoption of features exhibited by this our avatar (Ma et al., 2016; Zhang et al., 2021). This finding is consistent with previous research results, like the observed increase is of people's empathy after embodying a virtual version of Sigmund Freud (Osimo, Pizarro, Spanlang, & Slater, 2015) or increases in intelligence after embodying a virtual version of Albert Einstein (Banakou, Kishore, & Slater, 2018).

Even though the increase of subjective age after synchrony with the elderly avatar fits with our hypothesis, one may ask why we also found evidence for some increase of age after the asynchronous condition. We assume that the first-person perspective in both conditions supported identification with the avatar to some degree, which would also allow some part of the effect to occur in the asynchronous condition. According to previous findings, among the three factors which impact embodiment, first-person perspective itself is important for ownership illusions, irrespective of synchrony (Ma, Yang, & Hommel, 2023; Slater et al., 2009; Petkova, Khoshnevis, & Ehrsson, 2011). However, given that the increase of subjective age was higher in the synchronous condition, we can conclude that synchrony also contributed to the virtual aging effect.

Also as expected, the Simon effect was larger after the synchrony condition, which suggests that subjective aging had a similar effect as real cognitive aging (e.g., van der Lubbe & Verleger, 2002). Hence, virtual aging as a consequence of embodying an elderly

Table 2
Means and SEs (in brackets) of subjective age in the four conditions.

	Synchronous	Asynchronous
pre experience	23.11(0.81)	23.75(0.90)
post experience	29.63(1.23)	27.04(1.12)

Table 3
Reaction times and accuracy results of Simon task, mean and SE (in bracket) values, for the four conditions of synchrony and congruency.

Congruency	Reaction times (ms)		Accuracy (%)	
	synchronous	asynchronous	synchronous	asynchronous
congruent	470.31(13.61)	463.99(7.65)	96.84(0.58)	97.69(0.37)
incongruent	496.15(13.57)	483.96(7.13)	94.95(0.71)	95.72(0.55)

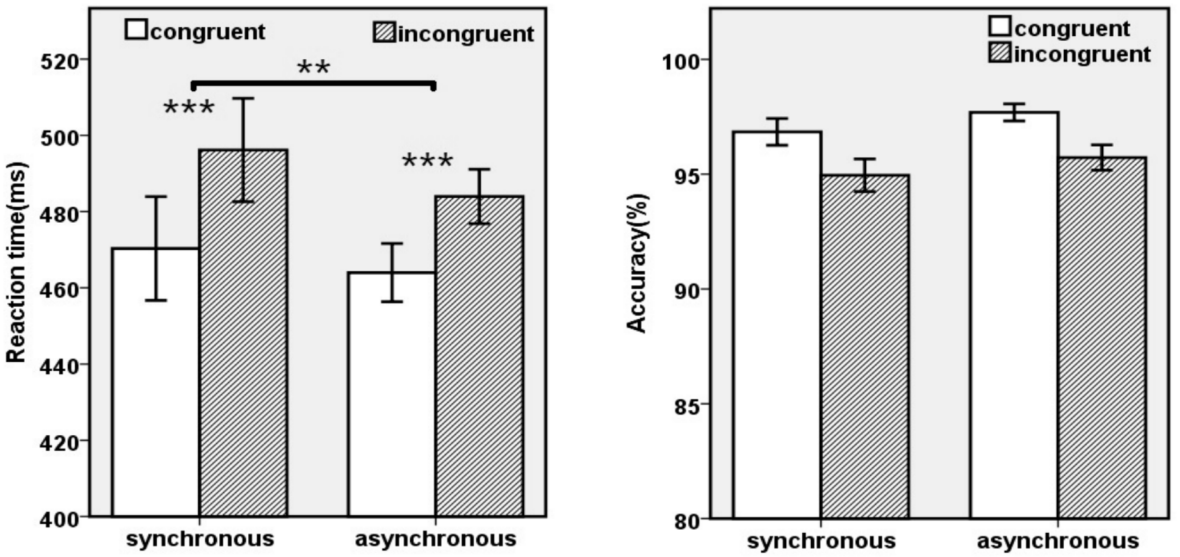

Fig. 5. Results of the Simon task, error bars represent +/- 1 SE.

avatar can make young college students behave like elderly participants. Or, more specifically, virtual aging affects people's control functions in similar ways as actual physiological aging would affect them. Given the nature of the Simon task, this can at least be concluded for a task that is tapping into the classical concept of cognitive control, by calling for metacontrol persistence (Hommel & Colzato, 2017). The next two experiments were devoted to testing whether this can be generalized to cognitive-control tasks that rely more on metacontrol flexibility.

3. Experiment 2. N-back task

Working memory updating denotes the dynamic ability to temporarily maintain and continuously refresh information during cognitive tasks – involving storage, manipulation, and retrieval processes (Baddeley, 2003; Diamond, 2013; Curtis, 2003; Klingberg, 2010). In Experiment 2, we examined whether the embodiment in an elderly virtual avatar may affect students' working memory updating performance, which was assessed by means of the N-back task (Owen et al., 2005; Schmiedek et al., 2009). Previous evidence on cognitive aging and working memory suggested that, older adults show a general decline in working memory performance, but also exhibit characteristics of functional reorganization and compensation (Schmiedek, Li, & Lindenberger, 2009). Neuroimaging evidence shows that high-performing older adults can keep their performance by recruiting additional prefrontal resources (Spreng, Wojtowicz, & Grady, 2010). Working memory aging can be viewed as a process involving both adaptation and decline, during which not only the cognitive aging, but also individual ability to employ different strategies, matters. In keeping with the traditional cognitive-control approach, as the same college participants embodied the virtual elderly face in our experiment synchronous or not, it is possible that only virtual aging contributes, thus our experimental hypothesis was as follows: compared to asynchronous conditions, in synchronous conditions participants should yield higher scores of illusory ownership towards the avatar, increased subjective age, lower accuracy and longer reaction time in the N-back task, especially in the more difficult 2-back condition.

3.1. Method

The method was as in Experiment 1, except for the cognitive-control task.

3.1.1. Participants

Sample size was determined the same as in Experiment 1. The participants were all from one University from China, 34 college students, 3 males and 31 females, were recruited through online announcements. The average age was 19.91 years old, with a standard

deviation (SD) of 1.31 and an age range of 17–23 years old.

3.1.2. N-back task

The two conditions of the N-back task were adopted from previous studies (Colzato et al., 2013). A stream of single visual numbers (from 0 to 9) was presented, stimulus-onset asynchrony was 2,000 ms, duration of presentation was 1,000 ms. Participants responded to targets (presented in 33 % of the trials) and to nontargets, with either "f" and "j" keys. Half of the participants pressed the "f" key in response to a target and the "j" key in response to a nontarget; the other half of the participants used the opposite mapping.

Target definition differed with respect to the two experimental condition. In the 1-back condition, targets were defined as stimuli that were identical to the preceding ones. In the 2-back condition, targets were defined as stimuli which matched to the one that was presented two trials before. Each N-Back task condition consisted of 10 practice trials followed by two blocks of 30 stimuli each. The sequence of the two conditions was fully counterbalanced across participants. Participants could take a rest between blocks. Feedback about reaction time and accuracy was presented in the practice trials, but not in experimental trials.

3.1.3. Design and procedure

The experiment used a three-factorial within-participants design. The first factor was synchrony (synchronous vs. asynchronous) between real and virtual faces, the second was N-back task type (1-back vs. 2-back), and the third was time (pre vs. post VR experience). The analytical strategy was as in Experiment 1.

3.2. Results

3.2.1. Embodiment questionnaire

Paired t-tests showed that, except for question Q6, $p = 0.101$; Q7, $p = 0.121$; and Q11, $p = 0.825$; also agency control, $p = 0.163$; the synchrony effect was significant for ownership and agency items, t(33)s>=2.30, ps<=0.028, ds > 0.39. Except for Q12, scores were all higher under synchronous conditions than asynchronous conditions. Table 4 and Fig. 6 show the participants' ratings of the ownership and agency questionnaire under both synchrony conditions.

The IOS results were also analyzed using paired *t*-test, and a significant synchrony effect was found, $t(33) = 7.660$, $p < 0.001$, $d = 1.31$: the IOS score was significantly higher after synchronous conditions ($M = 4.09$, $SE = 0.26$) than after asynchronous conditions ($M = 2.50$, $SE = 0.24$).

3.2.2. Subjective age

A significant main effect of time, $F(1,33) = 50.03$, $p < 0.001$, $p\eta^2 = 0.603$, BF10 > 100, indicated that the subjective age was significantly higher after the virtual experience ($M = 27.50$, $SE = 1.04$) than before ($M = 21.40$, $SE = 0.48$). The synchrony effect was not significant, $p = 0.862$; but the interaction was, $F(1,33) = 10.66$, $p = 0.003$, $p\eta^2 = 0.24$, BF10 = 15.38. Two-tailed paired t-tests showed that post-experience subjective age was significantly higher than pre-experience age, both in synchronous, $t(33) = 7.05$, $p < 0.001$, $d = 1.21$, BF10 > 100; and asynchronous conditions, $t(33) = 5.96$, $p < 0.001$, $d = 1.02$, BF10 > 100. Subjective age was equivalent in both synchrony conditions before the VR intervention, $p = 0.103$; but was significantly higher for synchronous than asynchronous conditions thereafter, $t(33) = 2.18$, $p = 0.037$, $d = 0.37$, BF10 = 1.46, only with anecdotal evidence. See Table 5.

3.2.3. N-back task

We calculated hit rate, false alarm, correct reject and miss rates, and the sensitivity index d' for each participant and condition. Notably, 100 % hit rates were adjusted using the formulas 1–1/(2n); and zero false alarm rates using 1/(2n), where n was the number of total hits or false alarms (Ma et al., 2021; Colzato et al., 2013). The repeated-measures 2(synchrony: synchronous vs. asynchronous) × 2(N-back types: 1-back vs. 2-back) within-participants ANOVA was carried out on the sensitivity index d', as well as RTs from valid trials. As the sensitivity index d' represents Accuracy according to the signal detection approach, we do not report the Accuracy results separately.

The ANOVA of the sensitivity index d' showed a significant main effect of N-Back task type, $F(1,33) = 46.43$, $p < 0.001$, $p\eta^2 = 0.59$, BF10 > 100, indicating that d' decreased in the 2-back ($M = 2.80$, $SE = 0.12$) as compared to the 1-back condition ($M = 3.62$, $SE = 0.07$). The main effect of synchrony and the interaction were not significant, ps > p = 0.53. See Table 6 and Fig. 7.

The ANOVA of RTs showed a significant main effect of N-Back task type, $F(1,33) = 77.51$, $p < 0.001$, $p\eta^2 = 0.70$, BF10 > 100, indicating longer RTs in the 2-back ($M = 708.15$, $SE = 23.29$) as compared to the 1-back condition ($M = 575.73$, $SE = 19.22$). The main effect of synchrony and the interaction were again not significant, ps > 0.32.

We then also analyzed the p(hit) and p(false alarm) separately. However, the results were the same as for the other measures: there were main effects of task condition, indicating a reduced hit rate and more false alarms in the 2-back condition, $F(1,33) = 25.48$, $p <$

Table 4
The questionnaire and agency results, the mean and SE (in blanket) values.

	Ownership (Q1-4)	Ownership control (Q5-Q6)	Agency (Q8-10)	Agency control (Q7, Q11-Q12)
synchronous	4.32(0.21)	3.46(0.29)	5.94(0.13)	2.91(0.22)
asynchronous	2.68(0.20)	2.93(0.26)	2.96(0.20)	3.27(0.20)

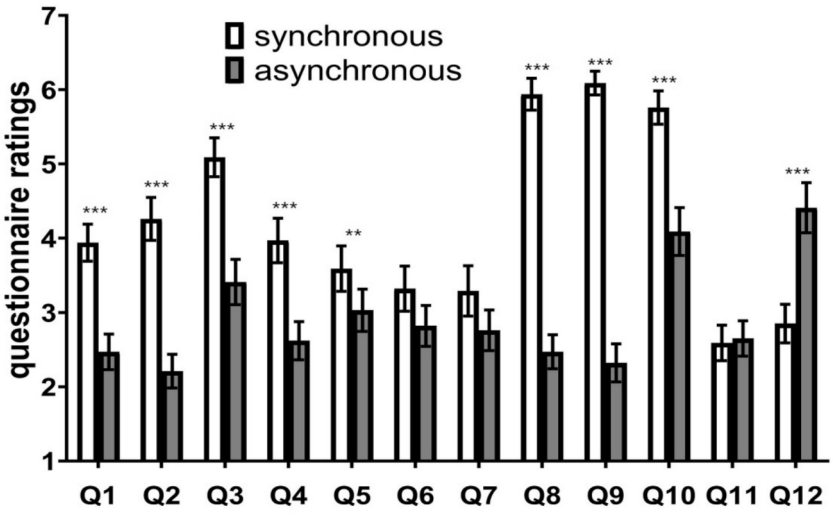

Fig. 6. The questionnaire results, error bar represents standard error.

Table 5
The mean and SE (in brackets) of subjective age in the four conditions.

	Synchronous	Asynchronous
pre experience	21.12(0.48)	21.68(0.53)
post experience	28.39(1.27)	26.60(0.93)

Table 6
Reaction times and d' results of N-Back task, mean and SE (in bracket) values, for the six conditions of synchrony and N-Back types.

	sensitivity index d'		Reaction times (ms)	
	synchronous	asynchronous	synchronous	asynchronous
1-back	3.63(0.10)	3.60(0.09)	566.52(20.23)	584.95(20.19)
2-back	2.85(0.15)	2.75(0.14)	702.14(26.35)	714.16(24.85)

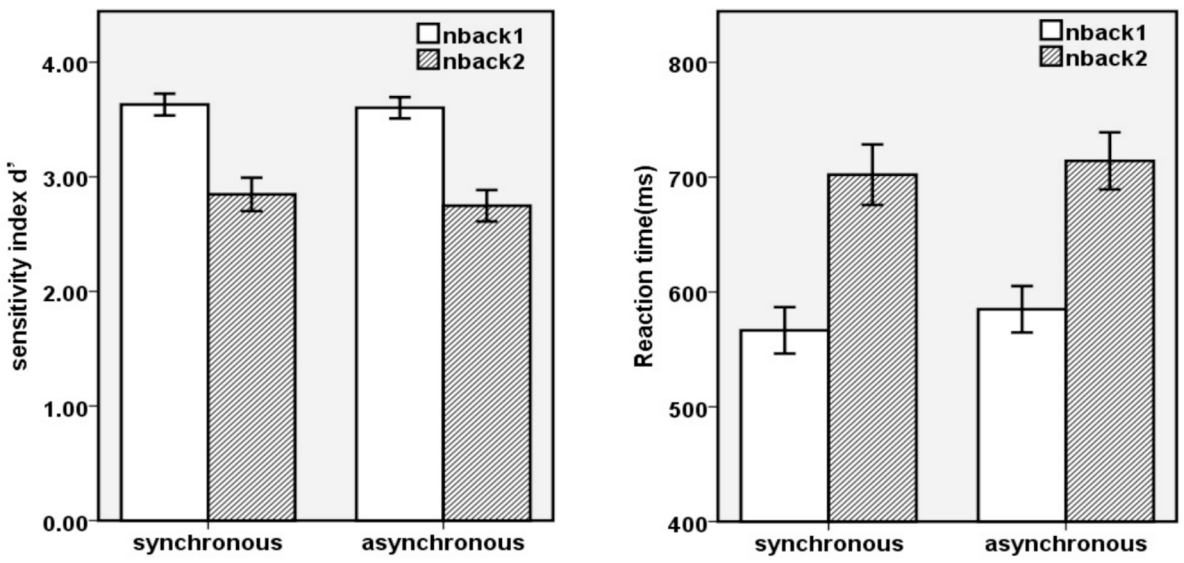

Fig. 7. Results of the Nback task, error bars represent +/- 1 SE.

0.001, $p\eta^2 = 0.44$; $F(1,33) = 26.51$, $p < 0.001$, $p\eta^2 = 0.45$, BF10s > 100; but no main effect of synchrony or interactions were obtained, ps > 0.80. See Table 7.

3.2.4. Correlation analysis

Similar to experiment 1, we analyzed the correlational relationships between ownership, agency ratings, sensitivity d' and RT results in the N-back tasks, also subjective age changes, separately for synchronous and asynchronous conditions.

Results showed that, when synchronous, significant correlations were found between RT in 1-Back and 2-Back, with $r = 0.716$, $p < 0.001$; and sensitivity d' in 1-Back and 2-Back, with $r = 0.334$, $p = 0.027$. Subjective age changes correlated to sensitivity d' in 2-Back, with $r = 0.373$, $p = 0.015$; to ownership, with $r = 0.392$, $p = 0.011$; and to agency, with $r = 0.330$, $p = 0.028$. When asynchronous, significant correlations were found between sensitivity d' and RT in 2-Back, with $r = -0.378$, $p = 0.014$; also between RT in 1-Back and 2-Back, with $r = 0.770$, $p < 0.001$. Ownership correlated to sensitivity d' in 2-Back, with $r = -0.335$, $p = 0.026$; to RT in 2-Back, with $r = 0.433$, $p = 0.005$; to RT in 1-Back, with $r = 0.383$, $p = 0.013$; to agency, with $r = 0.534$, $p = 0.001$. And, subjective age changes correlated to agency, with $r = 0.472$, $p = 0.002$. No other significant correlation was found, ps > 0.05.

3.3. Discussion

Consistent with Experiment 1, we found significant synchrony effects in the questionnaire and subjective age ratings in Experiment 2, suggesting that we successfully induced the embodiment of the elderly virtual avatar. The main effects of condition in the N-back task were also in agreement with previous research (Ma, Deng, Hommel, 2021), indicating that task difficulty had a significant effect on participants' working memory updating, possible because of the limited cognitive resources (Mattay et al., 2006). And yet, the expected interaction between task difficulty and synchrony was not observed.

On the one hand, this may be taken to stand in conflict with the obtained interaction in Experiment 1, which seemed to indicate that inducing an increase of subjective age makes university students exhibit the same control impairments that are shown by elderly participants. Given that age-related memory declines have been reported (Park et al., 2002), one may wonder why such declines were not successfully induced in Experiment 2. On the other hand, however, we note that most studies showing age-related memory declines were testing working memory span or capacity, but not updating—which our design was tapping into. Indeed, studies looking explicitly into the impact of aging on memory updating found little evidence for measurable effects (Basak & Verhaeghen, 2011; Verhaeghen & Basak, 2005).

Given that, from a metacontrol point of view, updating calls for metacontrol flexibility, but not persistence, the different outcomes of the two experiments might not so much indicate a failure to replicate but, rather, point to the importance of the metacontrol implications of the particular task being used. In other words, the increase of subjective age through embodying elderly avatars might impair performance on persistence-heavy tasks, as used in Experiment 1, but not performance on flexibility-heavy tasks, as employed in Experiment 2. To seek for independent evidence in support of this possibility, we carried out Experiment 3, which used another cognitive-control tasks that is tapping into metacontrol flexibility, rather than persistence.

4. Experiment 3. Task-switching

There is widespread consensus that the need to switch to another task, which requires a rewiring of stimulus–response mappings, is drawing heavily on cognitive-control resources (Kiesel et al., 2010). And yet, task-switching is unlikely to benefit from the control operations that would support successful performance in a Simon task. Rather than focusing on the currently relevant, and ignoring the currently irrelevant information, switching to a new task calls for the opposite: reminding oneself of the currently irrelevant, namely, the "other" tasks that one just suppressed in order to successfully complete the current trial. Hence, successful task-switching calls for metacontrol flexibility, rather than persistence, which is why theoretical models assume that task-switching performance relies on a different control factor then performance on Simon-type conflict tasks (Miyake et al., 2000). Indeed, a recent EEG study showed that the anticipated need to switch to a new task increases cortical noise—a marker of metacontrol flexibility (Yan et al., 2024), while conflict tasks like the Simon task consistently reduce cortical noise (e.g., Zhang et al., 2023).

Previous evidence on cognitive aging and task-switching suggest that, older people show declined cognitive flexibility, and larger switching cost (Wasylyshyn, Verhaeghen, & Sliwinski, 2011). Compared to middle-aged adults, older adults may engage in compensatory activation of the left insula (Zhu et al., 2014), and exert more cognitive effort to maintain cognitive flexibility (Li et al., 2023). Thus from a traditional approach to cognitive control, one would expect that task-switching performance should behave similarly to performance in Simon-type conflict tasks, so that the outcome of Experiment 3 should be comparable to that obtained in Experiment 1. But from a metacontrol point of view, however, one would expect that performance in Experiment 3 should show the

Table 7
The p(hit) and p(false alarm) results of N-Back tasks, mean and SE (in bracket) values, for the six conditions of synchrony and N-Back types.

	p(hit)		p(false alarm)	
	synchronous	asynchronous	synchronous	asynchronous
1-back	0.942(0.010)	0.946(0.008)	0.033(0.003)	0.036(0.004)
2-back	0.862(0.023)	0.854(0.017)	0.076(0.011)	0.076(0.011)

same signature as that obtained in Experiment 2. To test these predictions, we employed a typical task-switching design, in which participants were to switch between two different tasks. The switch cost in a task-switching paradigm manifests as significantly longer reaction times during task switches as compared to task repetitions (Kiesel et al., 2010; Badre & Wagner, 2006). Accordingly, the traditional approach would lead one to expect more pronounced switching costs in synchrony conditions (Zhu et al., 2014; Vera & Iring, 2014), whereas the metacontrol approach would predict comparable switching costs for synchrony and asynchrony.

4.1. Method

The method was as in Experiment 1, except for the cognitive-control task.

4.1.1. Participants

Sample size was determined the same as in Experiment 1. The participants were all from one university from China. 32 college students (10 males and 22 females) were recruited through online announcements. The average age was 19.91 years old, with a standard deviation (SD) of 3.13 and an age range of 18–24 years old.

4.1.2. Task-switching task

The task was adopted from previous studies (Huizinga et al., 2006; Swainson et al., 2003), which involved the maintenance and switching of the stimulus–response set. On each trial, one of two different figures (square or circle) was displayed and served as a cue, and then a varying number (1–9, except 5) was presented as stimulus on the screen. If the cue was square, participants needed to determine the parity of the number, press the "f" key when it was odd number, and press the "d" key when it was even number. If the cue was circle, participants needed to categorize the numerical size, press the "j" key if it was larger than 5, and press the "k" key if it was smaller than 5. In each trial, a fixation point was presented for 500 ms, the cue appeared for 1000 ms, the stimulus was presented for 1500 ms or until a response was given. The time interval between the two trials was 1000 ms.

If in two successive trials the cues were both the same figure, then the second trial was labeled as repeat trial; otherwise it counted as switch trial. In order to ensure that the numbers of repeated and switch trials were equally distributed and randomly presented, the trials were arranged in a pseudo-random manner. There were totally 30 practical trials, and experimental 80 repeat trials and 80 switch trials each. These trials were divided into four blocks, participants could take rest between blocks. Feedback about reaction time and accuracy was presented for the practical trials, but not for the experimental trials.

4.1.3. Design and procedure

The experiment used a three-factorial within-participants design. The first factor was synchrony (synchronous vs. asynchronous) between real and virtual faces, the second was task-switch task type (repeat vs. switch), and the third was time (pre vs. post VR experience). The analytical strategy was as in Experiment 1.

4.2. Results

4.2.1. Embodiment questionnaire

Paired t-tests showed that, except for question Q7, $p = 0.369$; and Q11, $p = 0.385$; the synchrony effect was significant for all other items, $t(31)>=2.712$, $p<=0.011$, $d>=0.479$. Except for Q12, scores were higher in synchronous conditions than in asynchronous conditions. Table 8 and Fig. 8 show the participants' ratings of the ownership and agency questionnaire under both synchrony conditions.

Paired t-tests of the IOS data showed a significant synchrony effect, $t(31) = 10.935$, $p < 0.001$, $d = 1.93$, indicating that the IOS score was significantly higher after synchronous conditions ($M = 4.91$, $SE = 0.21$) than after asynchronous conditions ($M = 2.66$, $SE = 0.20$).

4.2.2. Subjective age

There was a significant main effects of synchrony, $F(1,31) = 11.93$, $p = 0.002$, $p\eta^2 = 0.28$, $BF10 = 4.00$, indicating that the subjective age was higher under synchronous conditions ($M = 24.19$, $SE = 0.78$) than under asynchronous conditions ($M = 22.24$, $SE = 0.83$); and time, $F(1,31) = 15.90$, $p < 0.001$, $p\eta^2 = 0.34$, $BF10 > 100$, indicating that the subjective age was higher after the virtual experience ($M = 25.82$, $SE = 1.37$) than before ($M = 20.60$, $SE = 0.35$). The interaction, $F(1,31) = 12.46$, $p = 0.001$, $p\eta^2 = 0.29$, $BF10 = 83.33$, was also significant. Two-tailed paired t-tests found that subjective age was significantly higher after the VR intervention than before in both synchronous conditions, $t(31) = 4.99$, $p < 0.001$, $d = 0.88$, $BF10 > 100$; and asynchronous conditions, $t(31) = 2.27$, $p = 0.03$, $d = 0.40$, $BF10 = 1.75$, only with anecdotal evidence. Before the intervention, the two synchrony conditions did not differ, $p =$

Table 8
The questionnaire and agency results, the mean and SE (in blanket) values.

	Ownership (Q1-4)	Ownership control (Q5-Q6)	Agency (Q8-10)	Agency control (Q7, Q11-Q12)
synchronous	5.02(0.15)	4.33(0.28)	5.81(0.15)	3.11(0.19)
asynchronous	3.02(0.21)	2.67(0.23)	3.31(0.21)	3.87(0.20)

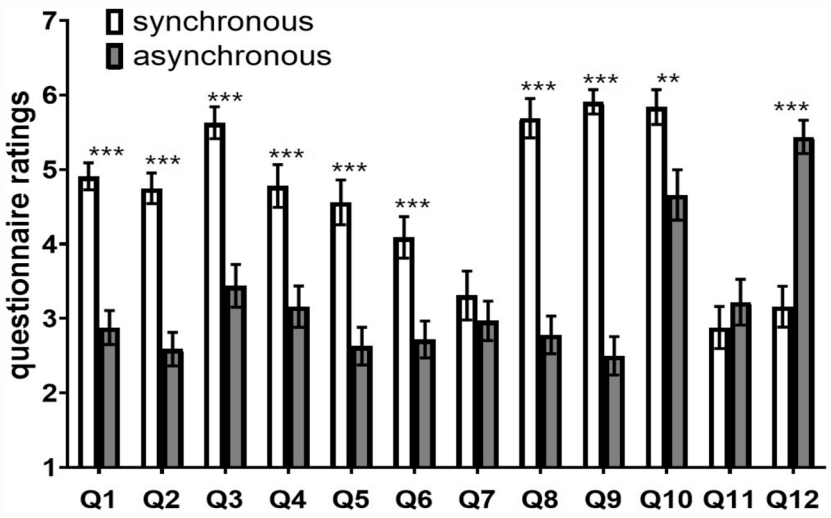

Fig. 8. The questionnaire and agency results, error bars represent +/-1 standard error.

0.377, but after the intervention, subjective age was higher for the synchronous conditions than for the asynchronous conditions, t(31) = 3.54, p = 0.001, d = 0.63, BF10 = 25.73. See Table 9.

4.2.3. Task-switching performance

RTs shorter than 100 ms were excluded. The descriptive statistics of RTs and accuracy are shown in Table 10. Repeated-measures 2 (synchrony: synchronous vs. asynchronous) × 2(condition: repeat vs. switch) within-participants ANOVA of the RTs yielded a significant main effect of condition, F(1,31) = 21.93, p < 0.001, $p\eta^2 = 0.41$, BF10 > 100, indicating longer RTs in switch (M = 747.07, SE = 29.67) than in repeat conditions (M = 702.61, SE = 26.63), suggesting typical task-switching effects. Neither the effect of synchrony nor the interaction was significant, ps > 0.15.

In the ANOVA analysis of the Accuracy, only the interaction was significant, F(1,31) = 4.85, p = 0.035, $p\eta^2 = 0.14$, BF10 = 2.26, while the main effects were not, ps > 0.12. Two-tailed paired *t*-test indicated that the synchrony effect was significant under switch conditions, with t(31) = 2.20, p = 0.035, d = 0.39, BF10 = 1.55, only with anecdotal evidence. No other effect was found, ps > 0.12.

We also computed the task switch cost by subtracting the RTs or error rates (1-accuracy) in repeat conditions from those in switch conditions. Two-tailed paired *t*-test analysis revealed that, for RTs, the synchrony effect was not significant, p = 0.159. For Accuracy, the synchrony effect was significant, with t(31) = 2.20, p = 0.035, d = 0.39, BF10 = 1.55, showing that the switch cost was higher in synchronous (M = 0.63, SE = 0.40) than asynchronous (M = −0.57, SE = 0.40) conditions, but only with anecdotal evidence. See Fig. 9 and Table 10.

4.2.4. Correlation analysis

Similar to experiment 1, we computed the task switch cost with RT and accuracy, using the subtraction between switch and repeat trials, and analyzed the correlational relationships between ownership, agency ratings, RT and Accuracy results in the task switch cost, separately for synchronous and asynchronous conditions. Results showed that, when synchronous, significant correlations were found between ownership and agency, with r = 0.528, p = 0.001. When asynchronous, significant correlations were found between ownership and agency, with r = 0.635, p < 0.001. No other significant correlation was found, ps > 0.05.

4.3. Discussion

Consistent with Experiment 1 and 2, the questionnaire and subjective age results in Experiment 3 suggested that we were successful in inducing virtual aging with our manipulation: after experiencing synchrony, young participants had the illusion of embodying the elderly virtual avatar and of being older. We also obtained typical task-switching effects, at least in RTs, which were higher in the switch than in repeat conditions. This is consistent with previous studies (Gajewski et al., 2018; Kray et al., 2004). With respect to the theoretically more interesting interaction between synchrony and task-switching, our findings were mixed: we obtained an impact of virtual aging on task-switching costs, which went into the predicted direction, but only in error rates, not in RTs. This provides only weak evidence for virtual-aging effects, because only the measure that did not replicate the basic task-switching costs was showing the expected interaction.

5. General discussion

In three experiments, we aimed to see whether embodying an elderly avatar by synchronizing people's own movements with those

Table 9
The mean and SE (in brackets) of subjective age in the four conditions.

	Synchronous	Asynchronous
pre experience	20.57(0.35)	20.64(0.37)
post experience	27.81(1.47)	23.84(1.49)

Table 10
Reaction times and accuracy results of Task-switch paradigm, mean and SE (in bracket) values, for the four conditions of synchrony and switch conditions.

	Reaction times (ms)		Accuracy (%)	
	synchronous	asynchronous	synchronous	asynchronous
Repeat	710.13(31.41)	695.08(25.42)	91.91(1.02)	92.94(0.89)
Switch	743.52(31.63)	750.61(31.19)	91.28(0.99)	93.50(0.74)

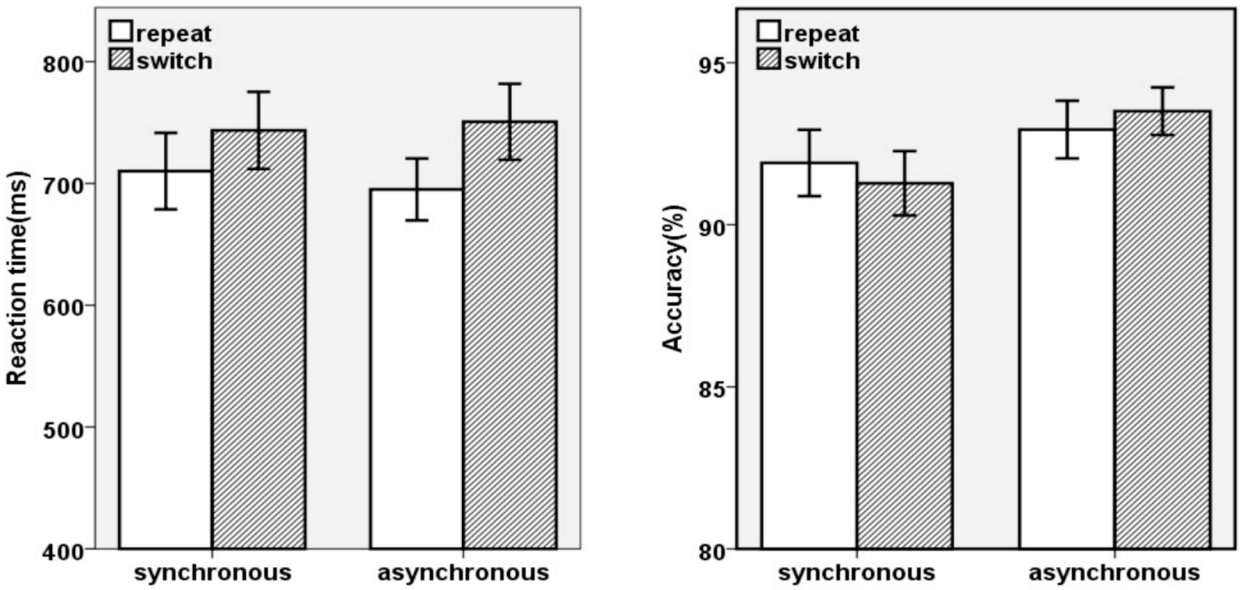

Fig. 9. Results of the Task-switching task, error bars represent +/- 1 SE.

of a virtual elderly person can generate effects that would also be expected from the impact of natural, physiological aging on cognitive control functions. Taken altogether, our observations suggest a number of conclusions.

First, as demonstrated by the findings regarding ownership and subjective aging, all three experiments provided strong support for the idea that subjective aging can be increased by embodying an elderly avatar. All three experiments indicate that our young participants felt significantly older after the embodiment manipulation. It is interesting to note that subjective age increased even after the asynchronous conditions, even though this increase was systematically smaller than in the synchronous conditions. This observation suggests that even under asynchronous virtual aging, participants can still develop a certain experience of becoming old, in the absence of a strong illusory ownership of the avatar (Domna et al., 2018). It is possible that the first-person perspective experience in itself can somehow induce feelings of immersive and connectedness, which was apparently sufficient to generate some degree of virtual aging.

Second, our results provide proof of principle that virtual aging can have similar effects on participants' cognitive-control functions as actual physiological aging. Synchronous multisensory information was sufficient for age-like control impairments in Experiment 1 and in the error rates of Experiment 3. Even though we do not consider the latter as particularly strong evidence, given that RTs, the commonly more sensitive measure, were unaffected; the former shows that virtual aging can be experimentally demonstrated in principle.

Third, however, the impact of virtual aging on cognitive control was not obtained for all types of tasks. It was obtained for the Simon task in Experiment 1, but not for the working-memory-updating task in Experiment 2 or the RTs in the task switching design of Experiment 3. The key question is, of course, why this might be the case. We speculate that this has to do with the kind of information on which virtual aging effects must be built. Clearly, virtual aging is mediated by aging stereotypes. After all, our participants did not really age but the manipulation must have triggered some representations about how it is to be old, which then affected performance.

The key question is where these representations are coming from. Obviously, they must come from knowledge and observations, which in turn begs the question of how visible cognitive-aging effects in physiologically older individuals are and under which conditions, in particular with respect to which tasks, elderly shows such effects.

This raises the possibility that persistence-heavy tasks, like the Simon task in Experiment 1, generate behavioral deficits in elderly individuals that are easier to spot by others, so that these deficits become a signature of aging. This may not hold, or hold less for memory updating and task switching, which may not suffer from physiological aging to the same degree. Indeed, metacontrol theory generally assumes that persistence is mainly driven by dopaminergic pathways of the prefrontal cortex, whereas flexibility is mainly driven by dopaminergic pathways in the striatum (Hommel & Colzato, 2017). Given that the prefrontal cortex is more strongly affected by physiological aging than the striatum is (e.g., Cools & d'Esposito, 2009), it would make sense that aging has a stronger, and easier to spot effect on control performance mediated by the prefrontal cortex than on functions that rely on the striatum. In other words, persistence-heavy tasks may be more diagnostic for visible aging effects than flexibility-heavy tasks. This may be the case for two, not necessarily mutually exclusive reasons: because persistence-heavy tasks are more strongly hampered by physiological aging than flexibility-heavy tasks, and because cognitive-aging effects are more visible for others when engaging in persistence-heavy rather than in flexibility-heavy tasks.

6. Limitations

We acknowledge some limitations of our study, which constrained the generalizability of our findings, and may inspire further research. Firstly, in all three experiments, the faces of the virtual characters were created by software, with average faces, rather than customized faces that would look like participants. This may lead to lower ownership illusions. In future studies, it would be an option to build more "personal" virtual faces. Secondly, the participants in this study were all college students. Considering that their physical and mental performance was likely to be relatively high, it is possible that such brief enfacement illusion experience may not show very strong effects. It is possible that somewhat older participants show different, stronger results after virtual aging. Thirdly, we employed the within participants experiment design, compared synchronous and asynchronous conditions, and the asynchronous condition served as the control condition (Sun et al., 2024). With this design, we can exclude the possible explanation from "only viewing the other elderly face for several minutes in VR may already impact our executive functions", and the observed significant difference between synchronous and asynchronous conditions can suggest that it is the "synchrony" and "embodiment" contribute to the changes of executive functions. But we admit that two additional baseline conditions may be needed in future studies. The first one is, a "younger face" condition, because we can then compare results in "younger face" and "elderly face" conditions. The second one is, a baseline for the Simon task before any embodiment condition, because then we can then see the extent of synchronous and asynchronous manipulations on cognitive-control tasks performance.

Open practices statement

Raw data of the study are available on the Open Science Framework (https://osf.io/jvfb3/); the Experiment was not preregistered.

CRediT authorship contribution statement

Ke Ma: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Min Wang:** Methodology, Data curation. **Bernhard Hommel:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article. All procedures performed in this study were in accordance with the ethical standards of the ethics committee of Southwest University (H25040), and with the 1964 Helsinki declaration and its later amendments. Informed consents were obtained from all participants included in this study.

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Data availability

Data will be made available on request.

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