

Research paper

Whose mind is it anyway? A systematic review and exploration on agency in cognitive augmentation

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ABSTRACT

Technologies for human augmentation aim to enhance sensory, motor, and cognitive abilities. Despite the growing interest in cognitive augmentation, the sense of agency and the feeling of control over one's actions and outcomes remained underexplored. We conducted a systematic literature review, screening 434 human–computer Interaction articles, and identified 27 papers examining agency in cognitive augmentation. Our analysis revealed a lack of objective methods to measure the sense of agency. We analyzed Electroencephalography (EEG) data of a dataset from 27 participants performing a Columbia Card Task with and without perceived AI assistance to address this research gap. We observed changes in EEG data for alpha and low-beta power, demonstrating EEG as a measure of perceived cognitive agency. These findings demonstrate how EEG can quantify perceived agency, presenting a method to evaluate the impact of cognitive augmentation technologies on the sense of agency. This study not only provides a novel neurophysiological approach for assessing the impact of cognitive augmentation technologies on agency but also leads the way to designing interfaces that create user awareness regarding their sense of agency.

1. Introduction

Today's technological advancements in wearable devices, sensing and actuation technologies, and Artificial Intelligence (AI) are driving the development of efficient human augmentation. Human augmentation technologies (HATs) refer to near-body, interactive technologies that enhance human performance and capabilities (Guerrero, da Silva, Fernández-Caballero, & Pereira, 2022; Raisamo, Rakkolainen, Majaranta, Salminen, Rantala, & Farooq, 2019; Villa, Niess, Nakao, et al., 2023). These technologies are already available to users and are mobile, such as Augmented Reality (AR) headsets (Sun, Huang, Wu, & Yang, 2022a), AI-powered glasses (Sapkota, Ram, & Zhao, 2021; Waisberg et al., 2024), or wearable Electroencephalography (EEG) (Schneegass et al., 2023). As framed by Raisamo et al. (2019), HATs can be divided into (i) sensory augmentation, which enhances human sensory abilities such as sight, hearing, touch, smell or taste; (ii) motor augmentation, which improves abilities related to bodily action, using actuation technologies; and (iii) cognitive augmentation (Stanney et al., 2009), which aims to extend people's cognitive abilities such as memory, attention, or problem-solving (Cinel, Valeriani, & Poli, 2019; Guerrero et al., 2022). Understanding and addressing people's experiences, behavior, and attitudes towards HATs presents a unique

opportunity for Human–Computer Interaction (HCI) to shape the future of technology in a way that is both human-centered and beneficial to society (Raisamo et al., 2019; Villa, Niess, Schmidt, & Welsch, 2023).

An essential factor that shapes the user's experience in HCI is the sense of agency. Sense of agency refers to the experience of controlling one's body and the external environment (Limerick, Coyle, & Moore, 2014). An issue that may arise with HATs is a perceived loss of agency by the user. In 1992, Friedman and Kahn (1992) examined problematic computing practices regarding human agency and suggested that humans inappropriately attribute agency to computers. Consequently, users may transfer responsibility from themselves to computing systems. Recently, Villa, Niess, Nakao, et al. (2023) found that society perceived users of HATs (“augmented humans”) differently if they were perceived to have little agency over the augmentation. Moreover, cognitive augmentations were perceived to be more dangerous than motor augmentations and elicited the least positive emotions (Villa, Niess, Nakao, et al., 2023). Consequently, it is important to understand the agency's role in cognitive HATs and learn how a sense of agency can be quantified using cognitive augmentation technologies.

Although literature reviews on body (Bennett, Metatla, Roudaut, & Mekler, 2023; Cornelio et al., 2022), action (Bennett et al., 2023;

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Cornelio et al., 2022; Moore, 2016), and augmentation in the context of human–computer integration (Cornelio et al., 2022) have been conducted, no review has specifically focused on human agency within the context of cognitive augmentation. Therefore, we systematically reviewed 20 years of HCI research, screening 434 papers through the lens of agency. Our review followed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Page, McKenzie, Bossuyt, Boutron, Hoffmann, Mulrow, Shamseer, Tetzlaff, Akl, Brennan, Chou, Glanville, Grimshaw, Hróbjartsson, Lalu, Li, Loder, Mayo-Wilson, McDonald, McGuinness, Stewart, Thomas, Tricco, Welch, Whiting, & Moher, 2021), including our search strategy and literature selection process. We chose the PRISMA method to ensure a systematic, transparent, and reproducible review process, enabling us to assess the limited research on the sense of agency in cognitive augmentation within ACM and IEEE databases. Subsequently, we analyze the role of agency in the found literature, which includes 27 research articles in the field of human augmentation and in four related domains: (i) neurotechnology, (ii) human–computer integration, (iii) Virtual Reality (VR) and Augmented Reality (AR), and (iv) AI and machine learning applications.

Drawing from the literature review, we identified a research gap: although sensory and motor augmentation technologies offer methods to assess the sense of agency during use, cognitive augmentation technologies have been largely overlooked in terms of real-time measures of perceived agency. Consequently, we analyzed an experiment with 27 participants who performed a Columbia Card Task (CCT), a risk-taking task, under two conditions: with and without a perceived AI-based cognitive augmentation assistant. We aimed to explore state-of-the-art research on agency in cognitive augmentation and to investigate methods for measuring the sense of agency.

While several studies on human augmentation measure a sense of agency via retrospective self-report scales, interviews, or intentional binding tasks (Kasahara, Nishida, & Lopes, 2019; Limerick et al., 2014; Tapal, Oren, Dar, & Eitam, 2017), these approaches often struggle to capture fast, within-task fluctuations in users' perceived control. They are usually applied at specific time points (e.g., after an interaction), risking the loss of fine-grained changes in experience. By contrast, some motor-augmentation work uses real-time neural indicators (Kang et al., 2015), yet this practice is rarely extended to purely cognitive tasks, where shifts in attention, memory, or decision-making could influence agency moment-by-moment. To bridge this gap, we critically examine how sense of agency has been studied across different augmentation domains and propose an EEG-based approach that exploits alpha and beta band activity to continuously track users' perceived control during cognitive augmentation—a methodology that contrasts with, and potentially enriches, existing self-report and behavioral measures.

The main contributions of this paper are as follows: (1) A systematic review of the agency in augmentation research, identifying key themes and research gaps; (2) An empirical analysis of the impact of perceived AI assistance on user agency, measured through neurophysiological EEG markers using the difference in activity between beta and alpha bands, with higher beta activity observed during perceived AI assistance. Our findings from the literature survey highlighted a research gap regarding the sense of agency for cognitive augmentation, emphasizing the need for further exploration in this area. Additionally, we show that EEG metrics commonly used in motor augmentation, such as differences in beta and alpha activity, can transfer to cognitive augmentation and potentially serve as a continuous real-time measure of perceived agency. These insights inform future research and the design of augmentation systems that prioritize and support user agency.

1.1. Research background and motivations

Below, we provide key definitions that guided our systematic review and data analysis. We summarize research on human and cognitive augmentation, as well as the sense of agency and its relationship with HATs.

1.1.1. Human augmentation

There is a growing number of research papers on human augmentation (i.e., also referred to as augmented human, human 2.0, or augmented humanity), yet the definitions differ across the scientific literature (Guerrero et al., 2022). Based on a literature review, Guerrero et al. (2022) infer that “Augmented humanity is a human–computer integration technology that proposes to improve capacity and productivity by changing or increasing the normal ranges of human function, through the restoration or extension of human physical, intellectual and social capabilities”. Similarly, Raisamo et al. (2019) define human augmentation as technologies that improve human productivity or capability, commonly focusing on “interactive digital extensions of human abilities”. More specifically, the authors define the research field of human augmentation as addressing methods, technologies, and their applications for enhancing a human's sensing, action, or cognitive abilities. This is achieved through sensing and actuation technologies, fusion and fission of information, and AI methods (Raisamo et al., 2019).

A related but different term is “human enhancement”, which is the broader field of utilizing natural or artificial means to improve human beings or human skills (Villa, Niess, Nakao, et al., 2023), by overcoming the current limitations of the human body (Raisamo et al., 2019). For instance, certain medications, surgeries, and genetic enhancement would fall under the umbrella of human enhancement. As a result, in the context of this paper, HATs are defined as near-body, interactive technologies that aim to directly enhance users' motor, sensory, and cognitive abilities.

1.1.2. Cognitive augmentation

Cognitive augmentation (i.e., augmented cognition (Fuchs, Hale, & Axelsson, 2007; Reeder, Cook, Meek, & Ozkaynak, 2017; Stanney et al., 2009)) refers to the use of HATs to enhance human cognitive abilities (Raisamo et al., 2019). This includes improving acquiring or generating knowledge and understanding of the world around us, for example, enhancing users' attention, memory, reasoning, problem-solving, or decision-making (Cinel et al., 2019). Prior research in cognitive augmentation has, for example, focused on memory augmentation using lifelogging (Dingler et al., 2021, 2016; Sellen et al., 2007) or neurofeedback training in VR (Accoto et al., 2021). Further research examples include smartwatches for health-related decision making (Reeder et al., 2017) and an “affective umbrella” wearable for emotion regulation (Chen et al., 2023).

Cognitive augmentation may utilize neuroscience technologies to record and act on brain activity. The most popular non-invasive neuroscience technologies to record brain activity are EEG, functional near-infrared spectroscopy, functional magnetic resonance imaging, and magnetoencephalography (see Cinel et al., 2019 for a review). To stimulate brain activity, common non-invasive technologies include transcranial electrical stimulation, transcranial magnetic stimulation, and focused ultrasound (Cinel et al., 2019). Only in the medical field, invasive methods such as deep brain stimulation to treat movement and memory impairments and electrodes implanted in the brain (to treat epilepsy) are frequently used (Cinel et al., 2019). In their review of neurotechnologies in the area of cognitive augmentation, Cinel et al. (2019) highlight the importance of tracking the ethical issues and implications of these technologies. One of those issues is the user's sense of agency (Cinel et al., 2019), which we define in the next section.

Definition #1 (Cognitive Augmentation): Cognitive augmentation seeks to enhance human cognitive performance and skills using near-body digital technologies that mediate the interaction of the individual with the self or the world. Such augmentation technologies do not assume control over the augmented human's task but instead serve as the user's subordinate (Raisamo et al., 2019; Villa, Niess, Nakao, et al., 2023).

1.1.3. Sense of agency

The sense of agency refers to the experience of controlling one's actions and their consequences (Limerick et al., 2014; Moore, 2016), allowing us to recognize ourselves as the agent of our behavior (Jeanerod, 2003).

HCI and cognitive neuroscience try to understand how people experience agency (Bennett et al., 2023; Limerick et al., 2014). For that, measures of agency have been constructed. Commonly, it is assessed with direct measures that explicitly ask participants to rate their subjective sense of agency with Likert scales on self-report questionnaires such as the *Sense of Agency Scale* (Tapal et al., 2017) or customized scales. Indirect measures of agency have also been proposed. Haggard, Clark, and Kalogeras (2002) introduced the “intentional binding effect” as an implicit measure of agency, which refers to a subjective compression of time between a voluntary action and its sensory consequence. This perceived time interval can be assessed with the Libet clock method (Libet, Gleason, Wright, & Pearl, 1993) or interval estimation (Engbert, Wohlschläger, Thomas, & Haggard, 2007).

In neuroscience, researchers also investigate objective, physiological measures of agency. Through human brain imaging, distributed networks related to agency can be studied (Wolpe & Rowe, 2014). Neurophysiological indicators have been shown to correlate with the sense of agency, enabling the continuous measurement of agency in real-time using EEG data (Jeunet, Albert, Argelaguet, & Lécuyer, 2018; Kang et al., 2015). Specifically, Kang et al. (2015) found that EEG alpha band activity, which is an important neural metric for information processing (Klimesch, 2012), to be the main neural oscillation of the sense of agency, suggesting the brain's anterior frontal lobe as an important area for generating agency. Further studies found that the sense of agency correlates with increased alpha and beta EEG power in the parieto-occipital regions, indicating that brain activity reflects changes in the sense of agency during hand movement with delayed visual feedback (Bu-Omer, Gofuku, Sato, & Miyakoshi, 2021). Another study using dual EEG setups in a dyadic context of role switching during imitation highlighted the role of alpha and beta frequency bands in distinguishing between self- and other-ascription of action primacy, showing the complex neural dynamics of agency in interactive settings (Dumas, Martinerie, Soussignan, & Nadel, 2012).

Beta frequency, similar to alpha frequency, is also significant in understanding the sense of agency. The modulation of local population activity and changes in functional connectivity, mediated by the beta band, indicate a network perspective of the sense of agency. One study found that during the belief of agency, the primary motor cortex (M1) shows stronger functional connectivity, mediated by the beta band, to the inferior parietal lobe and right middle temporal gyrus, suggesting a network supporting the sense of agency based on different causal beliefs (Buchholz, David, Sengemann, & Engel, 2019).

For example, neurotechnologies intervene between the user's intention and action and hence seem capable of altering human's sense of agency (Goering et al., 2021). For example, previous work by Haselager (2013) found that Brain-Computer Interfaces (BCIs) may disrupt the sense of agency, leading users to doubt their role in actions, concluding that awareness of this problem will help to solve it.

Definition #2 Agency in Cognitive Augmentation: Agency in human augmentation is an individual's sense of control and purposeful engagement with technological tools that enhance cognitive abilities. It means actively choosing, directing, and managing technological interventions that support personal cognitive functions like memory and decision-making, ensuring the person remains the primary driver of their enhanced capabilities (Bennett et al., 2023).

2. Literature review

This scientific background shows that the HCI community must be aware of users' potential loss of agency in human augmentation. We begin with a literature review to understand the sense of agency for HATs in the context of HCI. Several areas of augmentation often overlap in their implementation and practical approaches (Raisamo et al., 2019), providing transferable methodologies and frameworks that enhance the study of cognitive augmentation. Our paper aims to foster a holistic understanding of augmentation within HCI, emphasizing how lessons from motor and sensory domains can support and inform advancements in cognitive augmentation; thus, this literature review focuses on agency in cognitive augmentations but extends and draws insights from motor and sensory augmentations as part of the ecosystem of human augmentation technologies (Raisamo et al., 2019). We performed a systematic literature review following the guidelines from the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) (Page et al., 2021). The following sections describe the review's search strategy and selection process, experimental design, and conclusions.

2.1. Search strategy

The ACM Digital Library and IEEE Xplore electronic databases were searched for primary HCI studies on cognitive augmentation, which also measure or consider the sense of agency. On the ACM Digital Library, the content type “Research Articles” was selected. On IEEE Xplore, publications were filtered for “Journals” and “Conferences”. We considered records from 2003 to 2023 to focus on studies where cognitive augmentation technologies gained popularity. To allow for the reproducibility of search results, the exact search queries can be found in the Appendix in Table 1. After testing various keywords and combinations, we ultimately selected one specific search query that combined the terms “sense of agency” with “cognitive augmentation”, “augmented cognition”, or “human augmentation”, allowing us to obtain articles that use the established terms. Additionally, since human augmentation is not a well-defined term yet, we decided also to include a more descriptive query (see Query 2 in Table 1) which combined: (i) “sense of agency”, (ii) “augment*” or several synonyms, (iii) “cogniti*” or “brain”, and (iv) “human-computer interaction”, aiming to capture all relevant HCI articles, even if they do not mention the term “augmentation”. The “human-computer interaction” keyword was added to filter out records that lacked relevance to HCI research, as, without this addition, the volume of records was not manageable within our time constraints.

Through this search process, a total of 445 records were identified from the ACM Digital Library (n = 378) and IEEE Xplore (n = 67). Eight duplicate records were removed, which were caused by utilizing the two different search queries. Three records had to be removed because they were not research articles. In total, this resulted in 434 publications to be screened.

We focused our search on the ACM Digital Library and IEEE Xplore because these two databases comprehensively cover the main venues where peer-reviewed HCI and human augmentation research is typically published (e.g., CHI, UIST, TEI, IEEE VR, and related conferences and journals). While we recognize that additional databases (e.g., Web of Science, Scopus) might contain relevant work, our priority was to capture studies from the largest HCI-focused repositories. Moreover, preliminary exploration suggested that most primary HCI research on augmentation appears in these core platforms. Future reviews could expand beyond these databases to capture a broader range of interdisciplinary research, but for this work, we aimed to ensure depth and relevance within the HCI context.

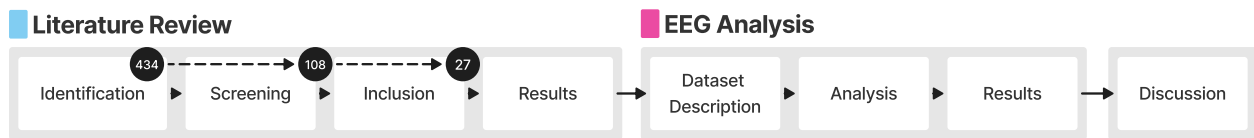


Fig. 1. Methodology Overview. We conducted a literature review to identify research gaps regarding cognitive agency. Afterward, we conducted a user study to investigate the subjectively perceived impact on cognitive user agency when interacting with an AI-driven assistant.

Table 1
Databases, search queries and number of identified records.

Database	Search query	Records
ACM Digital Library	Query 1: [All: "sense of agency"] AND [[All: "cognitive augmentation"] OR [All: "augmented cognition"] OR [All: "human augmentation"]]	10
	Query 2: [All: "sense of agency"] AND [[All: augment*] OR [All: improve*] OR [All: extend*] OR [All: enhance*]] AND [[All: cogniti*] OR [All: brain]] AND [All: "human-computer interaction"]	368
IEEE Xplore	Query 1: ("Full Text & Metadata": "sense of agency") AND (("Full Text & Metadata": "human augmentation") OR ("Full Text & Metadata": "cognitive augmentation") OR ("Full Text & Metadata": "augmented cognition"))	3
	Query 2: ("Full Text & Metadata": "sense of agency") AND (("Full Text & Metadata": "augment*") OR ("Full Text & Metadata": "improve*") OR ("Full Text & Metadata": "extend*") OR ("Full Text & Metadata": "enhance*")) AND (("Full Text & Metadata": "cogniti*") OR ("Full Text & Metadata": "brain")) AND ("Full Text & Metadata": "human-computer interaction")	64
		445

2.2. Selection criteria and process

We checked all identified publications ($n = 434$) against the following initial inclusion criteria:

1. Peer-reviewed, original work (excluding literature reviews)
2. Written in English
3. Sense of agency measured or considered
4. Focus on cognitive augmentation (i.e., HATs that aim to enhance cognition)

We included both quantitative and qualitative research and imported all records into Citavi (Software, 2020), version 6.7, to document databases and search queries. Although a single author conducted the initial screening and selection, decisions and exclusion reasons were recorded systematically, and any ambiguous cases were reviewed in consultation with another author to reduce potential bias.

The screening process (see Fig. 2) involved three phases: Identification, Screening, and Inclusion. In the first phase, we reviewed titles and abstracts, excluding 326 records. Unclear cases advanced to the second phase.

In the second phase, we reviewed the full texts of the remaining 108 publications, discarding those that failed to meet the inclusion criteria. However, following the described process, we found zero publications that met all initial inclusion criteria, as none of the studies specifically focused on cognitive augmentation.

Consequently, we extended inclusion criterion four to: "Focus on human augmentation or related domains from which insights on agency can potentially be transferred to cognitive augmentation". Following this change, we systematically re-screened the same 108 publications, applying the same stepwise procedure and documentation protocol used in the initial screening. In particular, the single reviewer again recorded the reasons for inclusion or exclusion, and any ambiguous cases were discussed with a second authoring order to ensure the re-screening process remained as rigorous and transparent as our initial review steps. As a result, we included 27 works in this review (see exclusion reasons in Fig. 2).

2.3. Results

In the following, we report the analysis of the 27 reviewed studies. We grouped them into cognitive, motor, and sensory augmentation topics based on the framework by Raisamo et al. (2019). Further studies that did not fall under these three categories, however, address agency in a context related to human augmentation, are presented in the *Agency in related domains* section (see Table 2 for an overview).

2.3.1. Agency in motor augmentation

Seven articles were identified that examine agency related to motor augmentation (Coyle et al., 2012; Kasahara et al., 2019, 2021; Shahu et al., 2022; Tajima et al., 2022; Venot et al., 2022).

Kasahara et al. (2019) developed a preemptive force-feedback system using electrical muscle stimulation (EMS) to enhance reaction time while maintaining the user's sense of agency. Their preemptive action approach with optimal timing (here, a tapping task with EMS actuation 160 ms after the visual target) yielded faster reaction times than participants' own reaction times and a higher sense of agency than traditional EMS methods, though voluntary actions still provided the highest sense of agency (Kasahara et al., 2019). Kasahara et al. (2021) extended their research with a reaction time experiment under three EMS conditions. Faster reaction times were retained post-EMS removal only when participants trained with optimal timing of preemptive action, suggesting that preserving agency improves motor adaptation after EMS training.

Yet, Kasahara et al. (2019) only considered scenarios of congruent situations when an alignment between user-driven and machine-driven touch exists. Given this limitation, Tajima et al. (2022) expanded upon this work by comparing assistive-touch and adversarial-touch in a force-feedback EMS study. They found that participants reported a higher sense of agency for favorable outcomes (assistive-touch) as compared to unfavorable outcomes (adversarial-touch). This suggests that the level of perceived agency is affected by an outcome bias. They also created the "agency-assistance trade-off matrix" (see Fig. 3), depicting design implications for haptic systems using actuators. Joint success (i.e., user and EMS correct) preserves some sense of

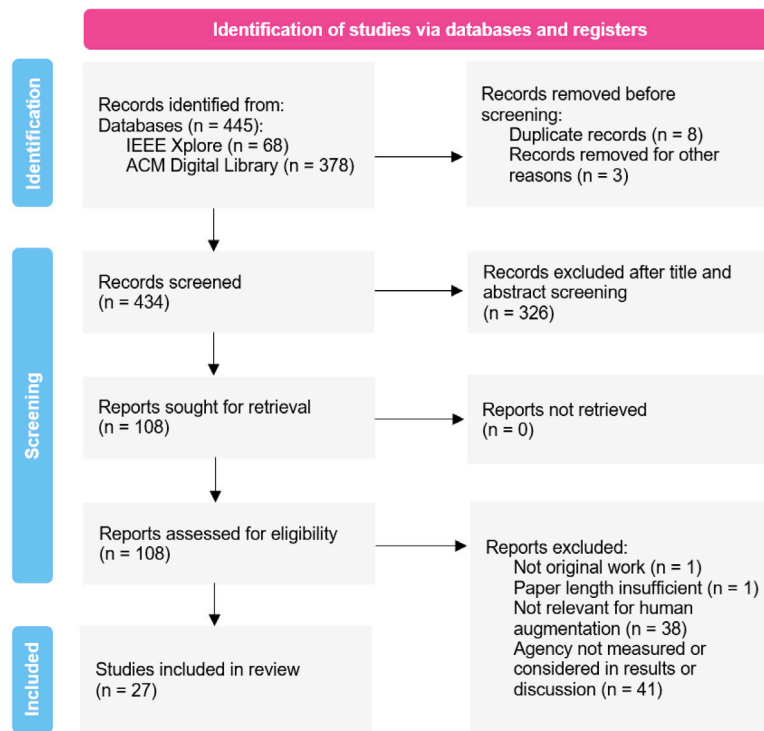


Fig. 2. PRISMA flow diagram of the literature review process. Source: Adapted from Page et al. (2021).

Table 2
Overview of literature included in review.

Section	Reference
Agency in cognitive augmentation	Semertzidis, Li Pin Hiuang, Vranic-Peters, and Mueller (2023)
Agency in motor augmentation	Coyle, Moore, Kristensson, Fletcher, and Blackwell (2012) Kasahara et al. (2019, 2021) Tajima, Nishida, Lopes, and Kasahara (2022) Shahu, Wintersberger, and Michahelles (2022) Venot et al. (2022)
Agency in sensory augmentation	Zolyomi and Snyder (2020)
Agency in related domains	
- Neurotechnology	Martinez, Benerradi, Midha, Maior, and Wilson (2022) Hougaard, Knoche, Kristensen, and Jochumsen (2022), Hougaard et al. (2021) Mercado-García, Alonso-Valerdi, Salas-Garza, López-Montoya, Garza-Ibarra, and Chávez-Madero (2021)
- Human-computer integration	Mueller et al. (2023)
- VR and AR	Gauthier, Albert, Martuzzi, Herbelin, and Blanke (2021) Zhang, Huang, Tang, Wang, and Yang (2022) Jun, Jung, Kim, and Kim (2018) Seinfeld, Feuchtner, Pinzek, and Müller (2022) Takada et al. (2022) Miura et al. (2021)
- AI and machine learning applications	Sun et al. (2022a), Sun, Huang, Wu, and Yang (2022b) Xu et al. (2023) Wang, Camacho, Jing, and Goel (2022) Thieme et al. (2023) Sali, Liu, Wardrip-Fruin, Mateas, and Kurniawan (2012) Sun, Song, Gui, Ma, and Wang (2023) Ahmad et al. (2022)

agency even with faster computer-driven touch, replicating previous studies (Kasahara et al., 2019, 2021). Forced success (i.e., user incorrect, EMS correct) involves corrective haptic assistance where the user involuntarily performs the correct action due to faster computer-driven touch, which hinders agency. Forced failure (i.e., user correct, EMS incorrect) should be prevented as it results in an incongruent as well as false outcome, whilst also diminishing agency. Joint failure (i.e., user and EMS incorrect) results in a negative outcome but could be useful for

adversarial touch, with the system taking the blame for failures when incorrect user-driven touch was predicted.

Shahu et al. (2022) examined EMS acceptance in four scenarios (motor learning, virtual reality, media player, and road safety), where one of the investigated factors was controllability (i.e., “a user’s capacity to control a situation (sometimes referred to as ‘sense of agency’)” (Shahu et al., 2022)). An online survey and interviews showed the highest acceptance for VR-EMS and the lowest for road safety, where loss of control was a negative factor. They recommend EMS systems maintain

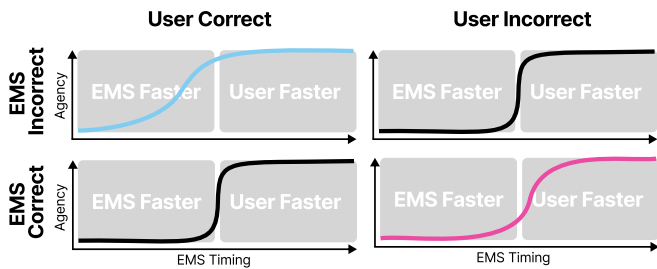


Fig. 3. Agency-assistance trade-off matrix.
Source: Adapted from Tajima et al. (2022).

user control and offer alternatives to preserve the sense of agency. Finally, Coyle et al. (2012) studied the impact of assistance levels (none/mild/medium/high) on agency in a machine-assisted point-and-click task with a gravity algorithm enhancing users' mouse movement. They found the highest sense of agency in no-assistance and mild-assistance conditions, with no significant difference between these two levels, indicating that computer assistance up to a certain level can still allow a high sense of agency. However, medium and high assistance significantly reduced agency. These findings suggest that assistance can lead to a loss of agency once a certain threshold is reached, which is relevant for human augmentation applications. So far, most identified studies on motor augmentation have focused on EMS technology. Venot et al. (2022) investigated a multimodal BCI, examining how the timing of motor imagery tasks affected performance. Their BCI integrated eye-tracking to enhance the overall sense of agency, which participants reported via a questionnaire. However, the authors did not report or discuss the agency results. In summary, these motor augmentation studies emphasize that the level of assistance and timing of the intervention are relevant factors for maintaining a sense of agency.

2.3.2. Agency in sensory augmentation

Research by Zolyomi and Snyder (2020) relates to sensory augmentation due to its focus on vision-enhancing technology. It is centered on understanding the social implications of digitally enhanced vision based on a head-mounted assistive device for low vision. In interviews with long-term users, the authors observed that users' desire to experiment with the assistive technology and their perception of its value was influenced by users' overall sense of agency in life (Zolyomi & Snyder, 2020). For future research on agency in cognitive augmentation, this suggests that considering a more holistic view of agency in life, rather than just during specific machine-assisted tasks, may lead to valuable insights.

2.3.3. Agency in related domains

In the following, we analyze the role of agency in domains related to human augmentation, grouped by (i) neurotechnology, (ii) human-computer integration, (iii) VR and AR, and (iv) AI and machine learning applications.

Neurotechnology. Neuroscience technology is commonly used to enhance human cognitive abilities (see Section 1.1.2). Cinel et al. (2019). Therefore, studies that do not investigate neurotechnology specifically for human augmentation but consider the role of agency is relevant here, as insights can likely be transferred to the design of cognitive HATs. A mixed-method study by Martinez et al. (2022) examined the ethical concerns for neurotechnology in the future workplace. Participants had generally positive attitudes towards future brain-scanning technologies, especially those boosting concentration (an example of cognitive augmentation). However, interviews revealed concerns about "trust and agency", particularly regarding devices that alter emotional states, which the authors suggest threaten users' sense of agency (Martinez et al., 2022). In the context of BCIs for stroke

rehabilitation, low BCI performance can decrease agency (Hougaard et al., 2021). Hougaard et al. (2021) found that fabricated input (i.e., preprogrammed positive feedback) increased perceived agency and reduced frustration in users in (i) a surrogate BCI based on eye blinks (Hougaard et al., 2021), (ii) a surrogate BCI study with stroke patients (Hougaard et al., 2022), and (iii) real motor imagery tasks in an online BCI study (healthy participants) (Hougaard et al., 2022).

Mercado-García et al. (2021) investigated whether the design approach impacts the modulation of EEG brain signals in a motor imagery task. They found that user-centered design (including a VR CAVE system) enhanced brain activity modulation compared to traditional Graz BCI design. The authors suggest that natural interactions that resemble BCI users' daily life activities offer them "a real sense of agency" (Mercado-García et al., 2021). However, users' agency was not measured, hence the benefit on agency is an assumption that needs further investigation.

Human-computer integration. According to Raisamo et al. (2019), human-computer integration, which uses computing resources and AI to support and work together with a human, is closely connected to cognitive augmentation. Hence, insights into agency in human-computer integration can likely inform cognitive augmentation research. Mueller et al. (2023) explored shared agency of bodily control in intertwined human-computer integration, using the "EduExo" exoskeleton with an electromyography sensor to support arm movement (i.e., motor augmentation). The user can access all system data on a laptop, making the machine's agency transparent. The authors present a framework with two key dimensions of intertwined systems (awareness and alignment of the machine's agency) and four system roles (angel, butler, influencer, adversary) (Mueller et al., 2023). Their framework supports designing cognitive augmentation systems with shared agency.

VR and AR. Human augmentation builds upon and draws elements from the fields of VR and AR (Raisamo et al., 2019). Therefore, examining the sense of agency in those contexts can be insightful for designing cognitive augmentation technologies.

Several identified VR studies that consider the sense of agency focus on embodiment (Gauthier et al., 2021; Jun et al., 2018; Miura et al., 2021; Seinfeld et al., 2022; Takada et al., 2022; Zhang et al., 2022). It was shown that embodying a body-matched virtual avatar as opposed to a virtual object increased participants' sense of agency during a cognitive task (Gauthier et al., 2021). Furthermore, avatar hand realism affected agency, with lower agency scores found for abstract hands compared to iconic or realistic hands (Zhang et al., 2022). Body continuity (i.e., whether the virtual hands and arms were disconnected or connected) showed no significant effect on perceived agency (Zhang et al., 2022). A VR study on the emotional effects of the full-body ownership illusion demonstrated that movement synchrony between virtual and real body led to increased emotional valence as well as increased sense of agency compared to a pre-recorded movement condition (Jun et al., 2018). Another VR study, in which motor tasks were performed, found that participants' sense of agency was higher in a virtual hand condition compared to a physical keyboard condition (without virtual representation) (Seinfeld et al., 2022). However, there was no significant difference in agency between virtual hands and virtual controllers (Seinfeld et al., 2022). In VR, it is also possible to embody multiple bodies simultaneously. In a "Parallel Embodiment" system developed by Takada et al. (2022), users play ping-pong while simultaneously controlling two robot arms. In a survey, users reported high ratings for the sense of agency over both robot arms despite visuomotor incongruences. However, some users suggested the robot arm itself had agency, with comments such as "the robot arm is moving on its own" (Takada et al., 2022). Takada et al. (2022) conclude that agency may be influenced by users' prior knowledge of another agent's presence. Furthermore, Miura et al. (2021) found that participants perceived agency over four virtual bodies in parallel when controlling them simultaneously. The results further suggest that self-reported

agency might have decreased with more bodies. In the context of object translation in handheld AR, Sun et al. (2022b) observed a higher subjective and objective agency in one degree of freedom compared to three degrees of freedom. Sun et al. (2022a) also revealed a negative association between mental workload and agency in head-mounted AR.

AI and machine learning applications. AI methods are an essential part of human augmentation (Raisamo et al., 2019), including memory augmentation (Dingler et al., 2021). For instance, AI assistants can efficiently carry out various tasks and make decisions for the user on their behalf. The model by Raisamo et al. (2019) for wearable augmentation proposes that AI is an enabling technology specifically for cognitive augmentation. Hence, the role of agency in AI and machine learning (ML) applications will be considered in the following since insights apply to cognitive augmentation. Xu et al. (2023) investigated explainable AI (XAI) in AR, proposing an XAI design framework based on a survey and expert workshops. To provide user agency, they recommend always making AI explanations accessible and offering detailed explanations upon request. In AI-mediated social interactions, Wang et al. (2022) developed an AI agent for online learning platforms assisting users in building social connections. An interview study revealed that students were concerned about losing agency over the connections they built. The authors suggest that a balance is required between ensuring successful interactions mediated by AI and preserving users' agency with whom to start a conversation. This aligns with findings from motor augmentation on the trade-off between assistance and agency (Coyle et al., 2012) (see Section 2.3.1). In healthcare, Thieme et al. (2023) developed an AI application to predict treatment outcomes in human-supported, internet-delivered Cognitive Behavioral Therapy (iCBT) for depression and anxiety. They found that AI design could affect clinical supporters' sense of agency and recommend that AI should inform the care rather than interfere with medical assessments, keeping the supporter in charge of examining patients' individual circumstances and potential reasons for the AI prediction outcome. Sali et al. (2012) explored natural language understanding (NLU) in games, finding that players reported more agency when the NLU interface provided pauses and prompts (as opposed to free-form text entry and reactive pauses), even if it limited their actions and free will. This suggests that guided actions can enhance the sense of agency. Moreover, Sun et al. (2023) found that users of automated machine learning systems actively exercise agency to overcome challenges in customizability, transparency, and privacy by employing workaround strategies. Finally, Ahmad et al. (2022) found that tangible controls, like hardware buttons, improve users' agency over smart voice assistants and their privacy. These insights could benefit cognitive HATs, such as voice-assisted memory extenders.

2.3.4. Agency in cognitive augmentation: A research gap

The systematic literature search identified no study that directly aimed at enhancing human cognitive capabilities (such as memory, problem-solving, attention, cognitive overload, etc.) using digital technology while also measuring or discussing the sense of agency. This research gap will be addressed in the discussion (see Section 4.3). One identified study closely related to cognitive augmentation was conducted by Semertzidis et al. (2023), who developed Dozer, a closed-loop wearable beanie that accelerates sleep onset through auditory and electrical brain stimulation. After an EEG detects drowsiness, the user's brain is stimulated through transcranial alternating current stimulation (TACS), and speakers play pink noise for sleep enhancement. In an in-the-wild study, the authors identified "closed-loop neurocentric agency" (Semertzidis et al., 2023) as a user experience theme related to bodily agency. The authors found that: (i) participants demonstrated high agency over the system despite feeling disconnected due to a lack of feedback, process understanding, and system familiarity. (ii) Knowledge of the system's function is important for experiencing agency. (iii) Bodily-integrated systems can provide a high sense of

agency without explicit user inputs (i.e., initiating causal influence over the system). Nevertheless, participants reported a diminished sense of body ownership and high awareness of the system's hardware, which compromised Dozer's ability to promote sleep onset effectively. Whilst aiming to accelerate sleep onset does not directly enhance cognitive capabilities, Dozer can be considered a cognitive augmentation technology in a broader sense. It targets cognitive processes involved in sleep regulation through a closed-loop wearable utilizing EEG, auditory, and electrical brain stimulation, thereby augmenting cognitive aspects related to sleep onset. Overall, this study implies that the user's understanding of the HAT's functionality may be relevant for maintaining a sense of agency. Yet, the specific field of sense of agency in cognitive augmentation remains largely unexplored.

2.4. Mapping the literature on agency on cognitive augmentation

Our literature review shows a research gap concerning the role of agency in cognitive augmentation technologies. This gap might reflect a underexploration of the topic within the HCI community, as existing publications have overlooked the real-time quantification of cognitive agency due to traditional focus areas or the limitations of our search to two databases.¹ While studies on agency in motor augmentation are relatively more prevalent (cf. Coyle et al., 2012; Kasahara et al., 2019, 2021; Shahu et al., 2022; Tajima et al., 2022; Venot et al., 2022), our findings suggest a notable disparity. Agency has been predominantly associated with motor control, defined as the subjective experience of control over one's actions (Moore, 2016). However, the concept of agency is equally important in cognitive augmentation. A diminished sense of cognitive agency can result in adverse outcomes, such as a dangerous shift in responsibility to the cognitive HAT (Friedman & Kahn, 1992) or increased risk-taking behavior (Villa, Kosch, Grelka, Schmidt, & Welsch, 2023). Addressing this gap is important for designing cognitive augmentation systems that appropriately balance human and technological control.

To advance understanding in this area, we leverage EEG data as an objective measure to investigate subjectively perceived cognitive agency. EEG provides a unique advantage by capturing real-time neural activity throughout an experiment, enabling continuous, objective agency measures. This contrasts with traditional questionnaires, which collect subjective, retrospective data and are limited to specific moments in the experimental process. Building on the EEG study by Villa et al. (2023), which explored the influence of external cues on causal beliefs in a risk-taking task, we focus specifically on how EEG-based neural correlates reflect cognitive agency. Participants in this study believed they were performing the task independently or with AI assistance, allowing us to manipulate their perceived sense of agency regarding perceived sense of agency. EEG has proven an efficient measure for assessing agency (Bu-Omer et al., 2021; Buchholz et al., 2019; Dumas et al., 2012; Kang et al., 2015), making it an ideal tool for estimating the perceived level of agency in real-time. Our analysis meets and exceeds recommended sample sizes by leveraging the open dataset by Villa et al. (2023) consisting of 27 participants completing 1080 trials. Trial counts for EEG research to ensure statistical power and reliable data quality (Boudewyn, Luck, Farrens, & Kappenman, 2018; Melnik et al., 2017). The re-analysis aimed to estimate if the sense of agency can be assessed in real-time when using cognitive augmentation technologies. This work highlights the relevance of EEG in agency research and lays the groundwork for designing cognitive HATs that prioritize the user's cognitive autonomy and responsibility.

¹ ACM Digital Library and IEEE Xplore.

3. Research model: Assessing the impact of perceived AI support on sense of agency

While the impact of technology on perceived agency attracted attention in HCI (Bennett et al., 2023; Cornelio et al., 2022; Coyle et al., 2012; Limerick et al., 2014), quantifying and understanding perceived cognitive agency remains a significant research gap. Our literature review indicates that neural activity is strongly linked to the perception of agency. Prior research has successfully utilized EEG to quantify agency perception, demonstrating that specific neural features serve as reliable indicators. For example, Kang et al. (2015) showed that alpha and beta band frequencies in the EEG are closely associated with the perception of agency. In their work, alpha and beta frequencies have been effectively used to capture variations in self-attributed actions, suggesting them as quantifiable real-time metrics for perceived agency in the study of agency. More importantly, research further demonstrates that these neural markers correlate with the subjective sense of agency (Yun et al., 2019). This section describes the data analysis of an EEG experiment that evaluated the perceived cognitive agency. In the following, we used an open dataset provided by Villa et al. (2023) to evaluate the feasibility of EEG data for assessing cognitive agency. While EEG has been extensively validated for motor agency through markers like Event-Related Potentials (ERPs) (Luck, 2014), the application of EEG to cognitive agency is less established, with potential overlaps between neural patterns of agency and those of attention or working memory (Bu-Omer et al., 2021; Kang et al., 2015). Despite these challenges, emerging evidence demonstrates that EEG can reliably capture neural correlates of cognitive agency, such as parieto-occipital alpha suppression and frontal theta activity, during decision-making and attribution tasks (Buchholz et al., 2019; Kang et al., 2015). Recent studies further suggest that EEG can differentiate self-generated from externally guided cognitive processes, including those involving AI assistance (Villa et al., 2023). To enhance reliability and applicability, future research should employ controlled experimental paradigms that isolate cognitive agency, address EEG's practical challenges through robust noise reduction and trial design, and triangulate results using complementary behavioral and subjective methods (Kirwan, Vance, Jenkins, & Anderson, 2023). By addressing these considerations, we evaluate EEG as a tool to measure cognitive agency, as previous research has used it to assess sensory and motor agency.

To achieve this goal, we analyzed an EEG experiment with 27 participants to understand the impact with and without perceived AI assistance (Villa et al., 2023) on cognitive agency (see Fig. 1). Although previous work showed that EEG is a validated and reliable measure for studying the sense of agency in motor augmentation (Bu-Omer et al., 2021; Dumas et al., 2012; Kang et al., 2015), EEG has not yet been extensively evaluated in the context of cognitive augmentation. Thus, the analysis investigates how EEG metrics, such as alpha and beta band activity, could form an alternative metric for quantifying agency in interactive systems.

3.1. Experimental design

The original study employed a within-subjects lab design focusing on one variable of interest: the verbal system description (DESCRIPTION). In the AI-ASSISTANCE condition, participants were told the system augmented cognitive skills, while in the NO-ASSISTANCE condition, no augmentation was claimed. Additionally, CCT (Columbia Card Task) task-related variables were collected: (1) LOSS CARDS (one vs. three loss cards), (2) WIN AMOUNT (10 vs. 30 points), and (3) LOSS AMOUNT (250 vs. 750 points). Verbal descriptions were counterbalanced, and CCT variables were randomized.

3.2. Dataset choice

The dataset provided by Villa et al. (2023) is well-suited for investigating changes in cognitive agency for several reasons. First, the experimental design in the dataset explicitly manipulated participants' expectations through verbal system descriptions, which prior research has shown to influence the sense of agency (Buchholz et al., 2019). The verbal manipulation allows for a systematic assessment of agency-related shifts, providing a foundation for analyzing neural correlates of agency. Second, extensive research demonstrates that EEG metrics, particularly oscillatory activity in the alpha and beta frequency bands, are reliable real-time markers for sensing changes in perceived cognitive agency. For example, studies have shown that alpha-band activity is associated with self-referential processing, an essential component of perceived agency (Yun et al., 2019). At the same time, beta-band oscillations reflect motor and cognitive processes underlying intentional control (Kang et al., 2015). Furthermore, neurophysiological evidence supports the relationship between EEG changes and agency perception across diverse contexts, including cognitive tasks. Our analysis bridges the gap for evaluating changes for the agency during cognitive augmentation through corresponding cortical activity using the existing experimental setup and EEG metrics from this dataset.

3.3. Task description

Participants played the Columbia Card Task (CCT) game according to Figner, Mackinlay, Wilkening, and Weber (2009). The CCT is a card game where players can win or lose points by flipping cards. Depending if the player flips a win or loss card, the player wins or loses points. The number of points influences the CCT a participant can win (i.e., 10 and 30 for win cards) or lose (i.e., 250 and 750 for loss cards). Players can flip another win card if they have flipped a win card before. The game round ends when the player flips a loss card. Overall, the participants played 20 rounds. At the start of each round, the cards were presented facing up (visible to the participants), then flipped down and shuffled at high speed so the participants could not follow them (Villa et al., 2023). The initial card placement is irrelevant as the game is manipulated: in win rounds, participants flip win cards until loss cards appear at the end of the deck, while in loss rounds, loss cards appear early.

Verbal system description. Prior work suggests that external cues can influence causal beliefs (self-attribution vs. external attribution), thereby modulating the sense of agency (Buchholz et al., 2019). We used this finding by analyzing participants' causal attributions through system descriptions. Specifically, participants were told to engage in the CCT task either in an AI-ASSISTANCE or the NO-ASSISTANCE condition. In the AI-ASSISTANCE scenario, participants were informed that a BCI monitored their brain activity and emitted inaudible binaural sounds (Colzato, Barone, Sellaro, & Hommel, 2017) to enhance visual processing and improve card selection accuracy. The cover story highlighted the cognitive benefits of these sounds, including their documented positive effects (Clements-Cortés, Ahonen, Evans, Freedman, & Bartel, 2016). Importantly, there was no active system in the practical implementation. In the NO-ASSISTANCE scenario (control condition), participants were told the augmentation technology was inactive, making their performance entirely reliant on their own skills in visualizing card movements and gameplay engagement.

3.4. Apparatus

Lab Streaming Layer (LSL) was used for time-series data capture, handling networking, time synchronization, and recording EEG streams with signal annotations. Tasks were performed on a Windows 10 desktop (HP Z1 G6, i7-10700 processor, 16 GB RAM) with a 27-inch monitor at 60 Hz. EEG data were annotated for each button press, including card flips and game round advances. Participants used a mouse to interact with the Columbia Card Task (CCT) while seated approximately 75 cm (29.5 inches) from the screen, adjusted to eye level.

3.5. Participants

Participants were recruited via university email lists and channels, excluding those with prior knowledge of EEG or human augmentation systems to prevent bias. Of 30 recruited individuals, one declined data use post-experiment, and two were excluded for missing expectancy ratings, leaving 27 participants ($N = 27$, 17 males, 10 females, $M = 29.13$, $SD = 9.51$). They reported moderate technical competence ($M = 4.76$, $SD = 1.43$). The study was approved by the German Psychological Society (DGPs) and the local ethics board (ID: EK-MIS-2020-023).

3.6. Experimental procedure

Participants were randomly assigned to either the AI-ASSISTANCE or NO-ASSISTANCE condition with balanced distribution. After a briefing on objectives and privacy measures, informed consent was obtained per the Declaration of Helsinki. Participants provided demographic data, rated technical proficiency on a seven-point Likert scale, and were introduced to human and cognitive augmentation concepts and equipment. Depending on their condition, they received a system overview and answered three comprehension questions. The CCT compensation model (0–10 euros based on performance) was explained, though all participants ultimately received the maximum compensation. Training included interface tutorials and loss scenario practice. An auditory threshold task was conducted to strengthen the association of causal beliefs, with participants either notified about the augmentation's inactivity or anticipating the system's (non-existent) sound output. Card selections and EEG data were collected during CCT sessions with counterbalanced conditions. After each session, the perceived performance improvements were assessed. Upon completion, they evaluated the augmentation system's usability, measured belief in the system functionality, provided a full debrief, and sought consent for data usage, ensuring compensation was not dependent on their decision.

3.7. Measurements

Previous work by Kang et al. (2015) has shown that Agency can be operationalized through alpha (8–12 Hz) and beta (12–15 Hz) band oscillations during motor tasks. In this analysis, we further test if this operationalization holds for cognitive agency; therefore, we study cognitive agency by evaluating the spectral behavior of the alpha and beta bands for objectively assessing perceived agency in real-time.

3.8. EEG recording and preprocessing

The authors collected EEG data at a sampling rate of 500 Hz using a LiveAmp amplifier (Brain Products, Germany) equipped with 32 water-based electrodes arranged according to the International 10–20 layout on an R-Net elastic cap. The electrode positions were as follows: Fp1, F3, F7, F9, FC5, FC1, C3, T7, CP5, CP1, Pz, P3, P7, P9, O1, Oz, O2, P10, P8, P4, CP2, CP6, T8, C4, FC2, FC6, F10, F8, F4, Fp2, and Fz. Impedance levels were maintained below or equal to 20 k Ω , with FCz serving as the reference electrode and FPz as the ground. Time synchronization was achieved using the Lab Streaming Layer² framework while preprocessing and analysis were conducted using the MNE-Python Toolbox (Gramfort et al., 2013). The authors applied a notch filter at 50 Hz and band-pass filtering between 1–30 Hz to eliminate high and low-frequency noise. The data was then re-referenced to the common average reference (CAR). We performed artifact detection and correction using an Independent Component Analysis (ICA) with the extended Infomax algorithm (Lee, Girolami, & Sejnowski, 1999) to mitigate the impact of attentional shifts, cognitive load, and fatigue. The labeling and rejection of ICA components were automated using the 'ICLabel' plugin within MNE (Pion-Tonachini, Kreutz-Delgado, & Makeig, 2019). The ICA-based preprocessing reduced artifacts related to fatigue, movement, and attentional shifts.

4. Experimental results

This section details our data analysis of the author's experimental study. We employed independent-sample t-tests for questionnaire items to establish statistically significant differences between the AI-assisted and no-assistance conditions. Conversely, we utilized generalized linear models (GLMs) to analyze the Spectral Analysis values. This choice facilitated the dissociation of the effects arising from the card type and those due to the experimental condition (AI-Assistance vs. No-Assistance). We first report the assessment of belief in augmentation functionality, followed by perceived performance improvements using a frequentist analysis as an alternative to the previously reported Bayesian analysis in Villa et al. (2023), and finally, the EEG spectral analysis.

4.1. Post-experiment assessment of belief in augmentation

Following the experiment and debriefing of the conditions used in the study, participants indicated their belief in the functionality of the augmentation system. Only 3.70% (1 out of 27) explicitly disbelieved the system's capabilities. While 40.74% (11 out of 27) reported minor suspicions, the majority (51.85%, 14 participants) fully believed in the augmentation technology's effect. One participant (3.70%) did not disclose their belief regarding the described functionality. The post-experimental perceived performance improvement questions revealed that participants, on average, perceived the augmentation system as facilitating task completion and enhancing performance and cognitive abilities. This perception further led them to believe in the system's potential for future development (see Table 3). These findings suggest that the provided cues effectively induced a sense of causality, likely due to the participants' belief in the system's functionality. Table 3 presents a summary of the statistics.

4.2. Spectral analysis

We initially assessed the spectral power at each electrode. The spectral power of each 1-second epoch was determined using the short-time Fourier transform (STFT) with a 512-point sliding Hanning window and 50% overlap. Subsequently, the results were averaged across trials for each condition and electrode. The averaged spectral power for each condition and electrode was then accumulated over two frequency bands: alpha (8–12 Hz) and low-beta (12–15 Hz). We selected 19 electrodes (FP1, FP2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, Pz, P3, P4, T5, T6, O1, O2) based on previous work (Kang et al., 2015). For further statistical analysis, the spectral power for each condition was computed in decibels and plotted on a topographical map (see Figs. 5 and 6).

In analyzing the effects of assistance condition and card outcome on Spectral Power, we employed a Generalized Linear Model (GLM) with a Gaussian family and an identity link function. The model for the alpha band revealed a statistically significant negative association between the presence of NO-ASSISTANCE and Spectral Power, with a coefficient of $-.13$ ($SE = .050$, $z = -2.63$, $p = .008$), indicating that Spectral Power decreased by $.13$ units when participants were informed that assistance is not provided, holding other factors constant (see Fig. 4). Similarly, the outcome of 'Win Card' was significantly associated with a decrease in Spectral Power by 1.38 units ($SE = .17$, $z = -7.99$, $p < .001$), compared to the baseline condition of 'Loss.'

The model identified a statistically significant negative association for the beta band between NO-ASSISTANCE and Spectral Power, with an estimated coefficient of $-.15$ ($SE = .052$, $z = -2.98$, $p = .003$), suggesting that Spectral Power decreased by $.15$ units when participants were informed that assistance was not provided. Conversely, the 'Win Card' outcome was significantly associated with a reduction in Spectral Power, evidenced by a coefficient of $-.95$ ($SE = .18$, $z = -5.30$, $p < .001$), indicating a substantial decrease in Spectral Power associated with winning outcomes.

² <https://labstreaminglayer.org>

Table 3

Items were answered on a 7-point Likert scale (1 — strongly disagree; 7 — strongly agree). The authors tested against an indecisive value of 3. Significantly different items are marked with *. The authors did not test the SUS against a hypothesized value.

Item/scale	<i>M</i>	<i>SD</i>	<i>t</i> (26)	<i>p</i>	<i>d</i>
<i>The game was easy to play.*</i>	3.93	1.86	2.59	.016	.50
<i>The cognitive augmentation has made the task easier.*</i>	3.74	1.40	2.74	.011	.53
<i>The cognitive augmentation has made the task more enjoyable.</i>	3.56	1.93	1.50	.146	.29
<i>The cognitive augmentation has made me more confident.</i>	3.67	1.86	1.86	.074	.36
<i>The cognitive augmentation has made me more efficient.</i>	3.52	1.50	1.79	.085	.34
<i>The cognitive augmentation has improved my performance.*</i>	4.11	1.55	3.72	<.001	.72
<i>The cognitive augmentation has improved my cognitive abilities.*</i>	3.93	1.54	3.12	.004	.60
<i>The cognitive augmentation in this game has a lot of potential for future development.*</i>	4.37	1.55	4.60	<.001	.89
System usability scale	56.94	11.34	–	–	–

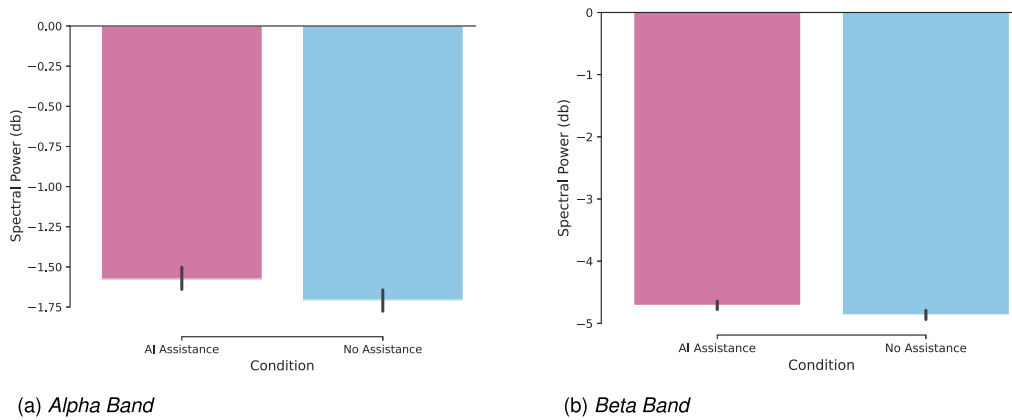


Fig. 4. Spectral Power for Alpha and Beta Bands: There is a decrease in spectral power for both frequency bands in the No-Assistance condition, suggesting a higher sense of agency.

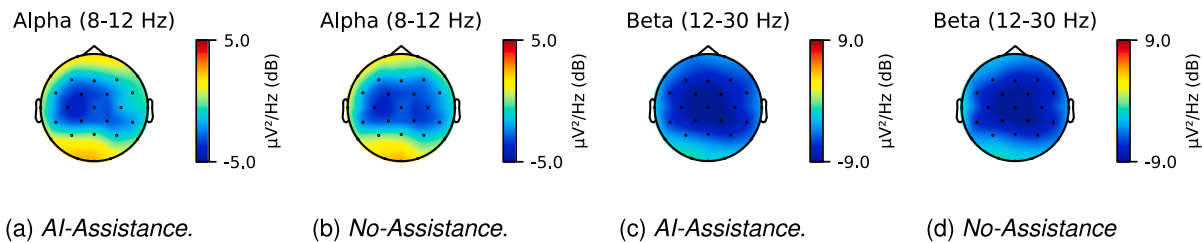


Fig. 5. Spectral Power Topographical Maps displaying Alpha and Beta frequencies under conditions with AI-Assistance and without AI-Assistance in the scenario of Win Cards.

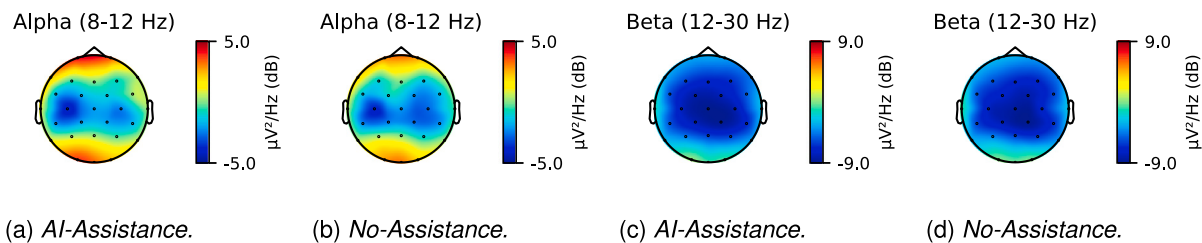


Fig. 6. Spectral Power Topographical Maps displaying Alpha and Beta frequencies under conditions with AI-Assistance and without AI-Assistance in the scenario of Loss Cards.

4.3. Discussion

In this section, we discuss and articulate the main findings of this paper, including mapping neurophysiological markers of agency in motor tasks for cognitive augmentation, its impact on agency, and future directions. For a broader overview of agency antecedents in HCI, see Bennett et al. (2023).

4.3.1. Quantifying sense of agency in cognitive augmentations

The analysis study on cognitive augmentation reveals how AI assistance affects users’ sense of agency through its electrophysiological data. Our findings reveal that participants experienced a significant decrease in the sense of agency when led to believe in the presence of AI assistance, as evidenced by shared variations in alpha and low-beta EEG power in the parieto-occipital regions. This suggests that the mere belief

in AI assistance can effectively lead to a diminished sense of agency in the context of cognitive augmentations at a neurophysiological level.

Compared to a baseline condition (No-Assistance), this outcome was observed through alterations in alpha and beta brain wave activities. Such findings highlight how perceived AI support can evoke different patterns in brain frequency that can allow discrimination across agency states. The decrease in the sense of agency aligns with the results reported by Bu-Omer et al. (2021), providing a neurophysiological basis for understanding how external cues and perceived technological interventions can modulate individuals' sense of control over their actions. This is in line with the call for disambiguating agency definitions in HCI as outlined in Bennett et al. (2023).

The findings also reveal that winning outcomes lead to a significant decrease in spectral power compared to losing outcomes across both frequency bands. This could indicate that successful outcomes, particularly in the context of the CCT, elicit a neurophysiological response associated with reduced cognitive load or decreased need for further action adjustment, as supported by Chen, Chaudhary, and Li (2022). This outcome delineates distinct brain activities during the anticipation and outcome phases of win and loss scenarios.

Winning outcomes can enhance the perception of having effectively influenced an event, i.e., "successful" agency. In situations where individuals believe AI is assisting them, this success can further shape their sense of control. Essentially, positive outcomes from tasks, when combined with the notion of AI support, refine how people perceive their influence over outcomes, reinforcing their sense of agency.

The new results expand on the role of alpha and beta on the sense of agency, as we introduced a new paradigm that was not explored before while still replicating results from previous work (Bu-Omer et al., 2021; Buchholz et al., 2019; Haggard et al., 2002). For instance, Buchholz et al. (2019) shows that the belief of agency itself changes the dynamics within sensorimotor networks, particularly highlighting how the beta band is modulated by one's causal belief about the origin of actions. This suggests that the decrease in beta frequency we observed might be not only a direct response to the AI assistance but also a reflection of the participants' altered belief systems regarding the control over their actions. Haggard et al. (2002) provides an overview of the sense of agency's underlying brain mechanisms, emphasizing the role of predictive processes and the contribution of alpha and beta waves in the sense of agency. This supports our findings from a theoretical standpoint, suggesting that the alterations in brain frequencies observed in our AI-assisted condition may reflect disruptions in the participants' prediction about their outcomes.

4.3.2. Individuals who believe being cognitively augmented present reduced agency

The observed effect in alpha and beta frequencies, indicative of a diminished sense of agency under perceived AI-Assistance, highlights a central consideration for HCI design: the need to maintain or enhance a user's sense of control and autonomy when interacting with intelligent systems. This consideration becomes especially pertinent as we explore the integration of neurophysiological markers of a sense of agency as an input for interaction, such as in BCIs. In rehabilitation, for instance, adaptive protocols could significantly improve recovery outcomes by aligning therapeutic activities with the patient's specific neural patterns, thereby reinforcing their sense of agency. Similarly, in educational technologies, learning experiences that adapt to the student's sense of agency could make education more engaging. The observed effect in alpha and beta frequencies suggests a decreased sense of agency, drawing a parallel to educational areas (Klemenčič, 2015). The authors discuss the importance of fostering intentional and reflective interactions between students and their environments, framed within their relational, cultural, and socio-economic contexts. This perspective aligns with our findings, highlighting the need to design intelligent systems that not only adapt to users' neural markers

of agency but also actively reinforce their sense of control and autonomy. In educational technologies, this means creating adaptive learning experiences that enhance students' agentic orientation and capacity by dynamically aligning with their cognitive and emotional states. By integrating neurophysiological markers as inputs, such systems could potentially improve student engagement by resonating with the temporally embedded and relational nature of agency, fostering deeper involvement and personalized trajectories in education (Klemenčič, 2015).

4.3.3. Neurophysiological insights into agency with cognitive augmentation

Our EEG findings demonstrate decreased alpha and beta spectral power with perceived AI assistance and, upon winning, elucidate the neurophysiological facets of agency within cognitive augmentation. This reveals how AI perceptions and outcomes affect users' neurophysiological states, influencing their sense of agency. These insights inform the design of HATs that enhance abilities while preserving autonomy. We argue that considering users' neurophysiological reactions to aid and feedback, we should aim to empower rather than overpower user experiences. The development and design of AI should consider how it affects users' sense of agency at a neurophysiological level. By considering this, Designers can create AI systems and applications that align with users' sense of agency and better control over the AI outcomes, ultimately leading to technologies that users accept more. Yet, it is important to consider that, as shown in this paper, using neurophysiological markers to measure the sense of agency is still experimental, and thus, its reliability is still to be shown; additionally, implicit methods for measuring agency might be not capture entirely the user's attitudes, behaviors and feelings during interaction.

4.3.4. Quantifying the sense of agency in real-time

In our analysis, we utilized an EEG-based spectral analysis and based on literature (Bu-Omer et al., 2021; Dumas et al., 2012; Kang et al., 2015), we demonstrated that the alpha and beta EEG metrics initially developed to measure sense of agency in a motor action context also can measure the sense of agency in Human-AI interaction. Further supporting this, Freeman, Mikulka, Prinzl, and Scerbo (1999) showed that EEG indices using alpha and beta bands could be employed in adaptive automation systems, where the system dynamically switched between manual and automatic modes based on changes in user engagement measured through these EEG metrics. Similarly, Prinzl III, Scerbo, Freeman, and Mikulka (1995) developed a bio-cybernetic system that utilized an EEG index based on beta and alpha bands to modulate operator engagement in real-time, demonstrating the feasibility of using these metrics for adaptive automation in cognitive tasks. This opens up new alternatives for HCI researchers to integrate real-time agency measurements in their experimental designs with the advancement of EEG devices.

4.3.5. Implications and future research directions

Based on the knowledge gained from our systematic review and analysis, we now draw future research directions to further investigate agency's role in cognitive augmentation.

Find the right balance between augmentation and agency. In the context of machine-assisted point-and-click tasks, it was possible to assist users up to a certain level (mild assistance) without harming their sense of agency. Still, a rapid drop of agency occurred once more assistance was provided (Coyle et al., 2012). A good balance between the level of AI assistance and agency preservation was also identified as a crucial factor in the context of building AI-mediated social connections (Wang et al., 2022).

This suggests that the level of intervention may fundamentally impact agency, a finding that can likely be transferred to cognitive augmentation. *We recommend that designers of cognitive HATs find the right balance between the augmentation level and the perceived agency level*

for their specific system. This will likely depend on the specific use case, how important a high sense of agency is for the user in the given context, and how a lower level of augmentation would affect the user and their surrounding. Hence, future research should investigate this trade-off between the level of augmentation and agency for different types of cognitive HATs in various contexts. If a distinct threshold exists after which agency is lost, it is important to identify it so that designers can make informed decisions. Finding this right balance, hence leaving the user in control to some extent, may also increase the acceptance rate of the augmentation technology (Shahu et al., 2022). Moreover, we suggest considering human–computer incongruent situations when designing cognitive HATs (Tajima et al., 2022). In particular, prevent forced failures by design, e.g., a surgeon using an augmentation technology in medical care. Avoid forced successes when agency preservation is highly important, but allow it in training and safety-critical scenarios.

Optimize intervention timing. The level of assistance and the exact timing of the intervention must be considered (Kasahara et al., 2019, 2021). For motor augmentation, it was found that early preemptive EMS actuation decreased the sense of agency. Identifying the optimal timing for preemption resulted in faster reaction times whilst preserving the user's agency to some extent (Kasahara et al., 2019), even after removing the EMS device (Kasahara et al., 2021).

Likely, the intervention timing is also highly relevant in maintaining agency over cognitive augmentation. Designers should carefully consider the exact moment the cognitive HAT assists the user. In future studies, this timing should be manipulated in controlled experiments to investigate whether a sweet spot exists in which users' cognitive performance can be enhanced whilst also experiencing a high sense of agency.

Examine agency in different types of cognitive enhancement. People appear to be most excited about brain-scanning devices that boost concentration; however, when emotional states are altered, they have trust and agency concerns, as this may threaten their sense of agency (Martinez et al., 2022). This indicates that the level of agency and amount of concern may depend on the cognitive ability that the system augments. We recommend that future research examines which types of cognitive abilities can be enhanced whilst maintaining users' agency.

Reduce cognitive load. In head-mounted AR, Sun et al. (2022a) revealed a negative association between mental workload and the sense of agency. Consequently, cognitive augmentation in AR, which aims to reduce users' cognitive load, may lead to a win–win situation of decreased mental burden whilst increasing agency at the same time. Although measuring cognitive load has been the focus of HCI and user experience research since decades (Kosch et al., 2023), further research is needed to establish the causal relationship between cognitive load and agency. Nonetheless, we recommend that designers aim to minimize cognitive workload.

Explain the system's functionality. Explanations of AI output were found to be crucial for fostering agency in AI systems (Xu et al., 2023). Similarly, users of a bodily-integrated sleep wearable expressed a desire to comprehend the system's functioning to attain a high sense of agency (Semertzidis et al., 2023). Therefore, in the design of cognitive HATs, consider providing adequate explanations to enable users to understand the system's operations and to foster a relationship of competency and trust (Semertzidis et al., 2023) between users and the system.

Consider ethics. Our research suggests EEG as a neurophysiological measure for assessing agency during cognitive augmentation in real-time. While our results can be used to create agency-adaptive interfaces that improve the experience of using cognitive augmentation technologies, ethical considerations regarding autonomy, privacy, or manipulation are being discussed in the research community (Cinel et al., 2019). For instance, deliberately reducing agency as a result of perceived AI support could lead to long-term changes in cognitive control and decision-making, potentially manipulating users' self-perception of

autonomy. The potential consequences, such as altering users' beliefs about their control over actions, must be carefully managed to avoid negative psychological outcomes. The handling of sensitive neurophysiological data also introduces privacy and security concerns (Gordon, 2024), such as the potential of correlating stimuli with measured neurophysiological activity to infer cognitive states. While the field of neuroethics discusses the ethical discourse of sensing and adapting to neurophysiological data (Hosseini & Kumar, 2020), the debate around agency has only started recently (Goering et al., 2021). Future research should explore, implement, and evaluate guardrails for ethically employing cognitive augmentation technologies that modulate agency.

Resolve performance issues in neurotechnology. BCI studies conducted by Hougaard et al. (2022, 2021) indicate that when individuals' sense of agency is already reduced due to low performance of the BCI, computer assistance in the form of preprogrammed, fabricated input can improve agency. It appears that negative consequences (here, reduced agency) of low technology performance are mitigated through increased reliance on computer assistance in the form of fabricated input. Moving forward, it is crucial to resolve the underlying performance issues (the cause of the problem) to enhance agency in BCIs, which may eliminate the need for fabricated input.

Use objective measures of agency. As no gold standard on measuring agency exists yet, we also looked at which agency measures were utilized in the reviewed studies. To assess agency, the majority of identified studies relied on subjective self-reports by asking participants to respond to an agency questionnaire (Sun et al., 2022a, 2022b; Venot et al., 2022), commonly a single-item 7-point Likert scale question (Kasahara et al., 2019, 2021; Sun et al., 2023; Tajima et al., 2022). In some of the included VR studies, the agency measure was included in a self-report questionnaire concerning embodiment (Gauthier et al., 2021; Miura et al., 2021; Takada et al., 2022; Zhang et al., 2022), ownership illusion (Jun et al., 2018), or general VR experience (Seinfeld et al., 2022).

Several of the studies included did not directly measure the sense of agency. Instead, agency was identified as a theme based on qualitative study results (Martinez et al., 2022; Mueller et al., 2023; Sali et al., 2012; Shahu et al., 2022; Thieme et al., 2023; Wang et al., 2022; Xu et al., 2023; Zolyomi & Snyder, 2020). However, four studies did not specifically measure the sense of agency (Mercado-García et al., 2021). Instead, some assessed user's perceived control (Ahmad et al., 2022; Hougaard et al., 2022, 2021). Only two studies utilized objective measures of agency. Coyle et al. (2012) assessed intentional binding as an implicit measure of the sense of agency, using the Libet clock method in one experiment and interval estimation in the other. Finally, only one study used physiological measures of agency based on EEG data, applying spectral power analysis and brain activity analysis (Sun et al., 2022b).

The advantage of objective agency measures is that they do not rely on introspection and subjective reports, whereas self-reported agency can be biased and confounded (Wolpe & Rowe, 2014). In future studies, we recommend enhancing objectivity by combining subjective measures such as questionnaires with objective, physiological measures of agency (Wolpe & Rowe, 2014), for example, using EEG data (Jeunet et al., 2018; Sun et al., 2022b), as our results have shown that state-of-the-art EEG correlates for sense of agency apply for the context of cognitive augmentation. Therefore, we recommend that researchers include neurophysiological measures when assessing the sense of agency during cognitive augmentation.

4.3.6. Limitations

While this review aims to examine the agency's role in cognitive augmentation, most publications in our review are related to motor augmentation and other domains related to augmentation, such as neurotechnology, AR/VR, and AI. Based on insights from these related studies, we formulated research directions for cognitive HATs.

However, further lab-controlled experiments are required to validate whether our review findings can be transferred to cognitive augmentation. Another limitation is that, although we developed a clear inclusion criteria set, a single reviewer conducted the screening, which may introduce subjective bias despite our steps to consult a second author for ambiguous cases. Furthermore, we limited our database search to ACM Digital Library and IEEE Xplore for their strong HCI coverage, but this scope may have excluded relevant interdisciplinary work found elsewhere.

The analyzed dataset employed EEG as a physiological measure of agency, offering valuable insights. However, the limitations of EEG technology, particularly its cost and obtrusiveness, restrict its applicability in real-world HCI settings. Future research should investigate alternative physiological correlates of agency that are more ecologically valid and suitable for integration into consumer devices. Promising alternatives include exploring measures such as heart rate variability, electrodermal activity, and pupil dilation, which offer the potential for unobtrusive and cost-effective assessment of agency in diverse HCI contexts.

We acknowledge that EEG-based band measures (e.g., alpha band) can be influenced by several confounding factors such as attentional shifts, cognitive load, and fatigue (Klimesch, 2012). To mitigate these issues, we employed within-subject comparisons and counterbalancing in our experimental design and used ICA-based preprocessing to reduce artifacts related to fatigue and movement. Nonetheless, we emphasize that in future work, EEG should be interpreted in conjunction with behavioral and subjective data to robustly infer agency. Future work should consider triangulating EEG with additional metrics such as pupillometry, galvanic skin response, or self-report scales (e.g., intentional binding tasks or real-time Likert ratings) to provide a more comprehensive view of user agency.

While this analysis employed objective EEG measures to measure agency, it did not employ an explicit self-reported measure like the Sense of Agency Scale (Tapal et al., 2017). This deliberate choice aimed to avoid sensitizing participants to the specific assessed metric, as the original authors were concurrently manipulating causal attribution through verbal descriptions. However, this approach may have limited the ability to directly compare our findings with existing literature that relies on self-reported measures. This study utilized objective EEG measures to assess agency, deliberately avoiding explicit self-reported measures, such as the Sense of Agency Scale (Tapal et al., 2017). This decision was made to prevent participants from becoming sensitized to the specific evaluated metric, particularly as causal attribution was being concurrently manipulated through verbal descriptions. However, this approach may have limited the ability to directly compare our findings with prior research that relies on self-reported measures. Future studies could explore the integration of objective and subjective measures to gain a more comprehensive understanding of agency in similar contexts. Such an approach would shed light on the relationship between explicit self-reports and implicit measures of cognitive agency. This is especially compelling given related research on motor augmentations, which has demonstrated correlations between implicit metrics and self-reported measures (Yun et al., 2019).

5. Conclusion

Human agency in the context of cognitive augmentation technologies remains an under-explored area despite its critical importance in HCI. This work addresses this gap by reviewing two decades of HCI research on agency and related domains. The analysis reveals a lack of studies directly investigating the sense of agency within cognitive augmentation. Drawing upon insights from the reviewed literature, we propose future research directions to advance the understanding of agency in this context. Furthermore, we present an analysis of an experimental study exploring whether EEG-based agency metrics originally developed for a motor action context can capture the sense of agency in

cognitive augmentation. Our findings demonstrate the feasibility of this approach and reveal a decrease in perceived agency when participants are explicitly informed about AI assistance. In the future, specific factors that support or hinder agency, for instance, considering (i) a balance between assistance and agency preservation, (ii) intervention timing, and (iii) different types of cognitive enhancements, should be explored further.

CRedit authorship contribution statement

Steeven Villa: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lisa L. Barth:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Chioffi:** Writing – review & editing. **Robin Welsch:** Writing – review & editing, Investigation, Formal analysis. **Thomas Kosch:** Writing – review & editing, Writing – original draft, Supervision.

Ethic approval information

The German Psychological Society (DGPs) and the local institutional ethics board provided ethical approval for the study: Ethical assessment ID: EK-MIS-2020-023.

Declaration of competing interest

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.

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