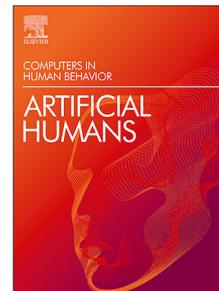# Journal Pre-proof

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

Steeven Villa, Lisa L. Barth, Francesco Chiossi, Robin Welsch, Thomas Kosch

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1   **Whose Mind is it Anyway? A Systematic Review and Exploration on Agency in Cognitive**

2   **Augmentation**

3   Anon[1] and Anon[2]

4   [1]Anon

5   **Abstract**

6   Technologies for human augmentation aim to enhance sensory, motor, and cognitive abilities. Despite the

7   growing interest in cognitive augmentation, the sense of agency and the feeling of control over one's

8   actions and outcomes remained underexplored. We conducted a systematic literature review, screening

9   434 human-computer Interaction articles, and identified 27 papers examining agency in cognitive

10 augmentation. Our analysis revealed a lack of objective methods to measure the sense of agency. We

11 analyzed Electroencephalography (EEG) data of a dataset from 27 participants performing a Columbia

12 Card Task with and without perceived AI assistance to address this research gap. We observed changes

13 in EEG data for alpha and low-beta power, demonstrating EEG as a measure of perceived cognitive

14 agency. These findings demonstrate how EEG can quantify perceived agency, presenting a neurological

15 method to evaluate the impact of cognitive augmentation technologies on the sense of agency. This study

16 not only provides a novel neurophysiological approach for assessing the impact of cognitive augmentation

17 technologies on agency but also leads the way to designing interfaces that create user awareness

18 regarding their sense of agency.

19   *Keywords:* Sense of Agency, Cognitive Augmentation, Human Augmentation, Augmented Human,

20 Human-Computer Interaction

Whose Mind is it Anyway? A Systematic Review and Exploration on Agency in Cognitive Augmentation

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 et al., 2022; Raisamo et al., 2019; Villa, Niess, Nakao, et al., 2023). These technologies are already available to users and are mobile, such as Augmented Reality (AR) headsets (W. Sun et al., 2022a), AI-powered glasses (Sapkota et al., 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 et al., 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 et al., 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 et al., 2023; Cornelio et al., 2022), action (Bennett et al., 2023; 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

53 agency within the context of cognitive augmentation. Therefore, we systematically reviewed 20 years of

54 HCI research, screening 434 papers through the lens of agency. Our review followed the Preferred

55 Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Page et al., 2021),

56 including our search strategy and literature selection process. We chose the PRISMA method to ensure a

57 systematic, transparent, and reproducible review process, enabling us to assess the limited research on

58 the sense of agency in cognitive augmentation within ACM and IEEE databases. Subsequently, we

59 analyze the role of agency in the found literature, which includes 27 research articles in the field of human

60 augmentation and in four related domains: (i) neurotechnology, (ii) human-computer integration, (iii) Virtual

61 Reality (VR) and Augmented Reality (AR), and (iv) AI and machine learning applications.

62   Drawing from the literature review, we identified a research gap: although sensory and motor

63 augmentation technologies offer methods to assess the sense of agency during use, cognitive

64 augmentation technologies have been largely overlooked in terms of real-time measures of perceived

65 agency. Consequently, we analyzed an experiment with 27 participants who performed a Columbia Card

66 Task (CCT), a risk-taking task, under two conditions: with and without a perceived AI-based cognitive

67 augmentation assistant. We aimed to explore state-of-the-art research on agency in cognitive

68 augmentation and to investigate methods for measuring the sense of agency.

69   While several studies on human augmentation measure a sense of agency via retrospective

70 self-report scales, interviews, or intentional binding tasks (Kasahara et al., 2019; Limerick et al., 2014;

71 Tapal et al., 2017), these approaches often struggle to capture fast, within-task fluctuations in users'

72 perceived control. They are usually applied at specific time points (e.g., after an interaction), risking the

73 loss of fine-grained changes in experience. By contrast, some motor-augmentation work uses real-time

74 neural indicators (Kang et al., 2015), yet this practice is rarely extended to purely cognitive tasks, where

75 shifts in attention, memory, or decision-making could influence agency moment-by-moment. To bridge this

76 gap, we critically examine how sense of agency has been studied across different augmentation domains

77 and propose an EEG-based approach that exploits alpha and beta band activity to continuously track

78 users' perceived control during cognitive augmentation—a methodology that contrasts with, and potentially

79 enriches, existing self-report and behavioral measures.

80   The main contributions of this paper are as follows: (1) A systematic review of the agency in

81 augmentation research, identifying key themes and research gaps; (2) An empirical analysis of the impact

82 of perceived AI assistance on user agency, measured through neurophysiological EEG markers using the

83 difference in activity between beta and alpha bands, with higher beta activity observed during perceived AI

84 assistance. Our findings from the literature survey highlighted a research gap regarding the sense of

85 agency for cognitive augmentation, emphasizing the need for further exploration in this area. Additionally,

86 we show that EEG metrics commonly used in motor augmentation, such as differences in beta and alpha

87 activity, can transfer to cognitive augmentation and potentially serve as a continuous real-time measure of

88 perceived agency. These insights inform future research and the design of augmentation systems that

89 prioritize and support user agency.

90 **1.1. Research Background and Motivations**

91   Below, we provide key definitions that guided our systematic review and data analysis. We

92 summarize research on human and cognitive augmentation, as well as the sense of agency and its

93 relationship with HATs.

94 **1.1.1. Human Augmentation** There is a growing number of research papers on human augmentation

95 (i.e., also referred to as augmented human, human 2.0, or augmented humanity), yet the definitions differ

96 across the scientific literature (Guerrero et al., 2022). Based on a literature review, Guerrero et al. (2022)

97 infer that "Augmented humanity is a human-computer integration technology that proposes to improve

98 capacity and productivity by changing or increasing the normal ranges of human function, through the

99 restoration or extension of human physical, intellectual and social capabilities." Similarly, Raisamo et al.

100 (2019) define human augmentation as technologies that improve human productivity or capability,

101 commonly focusing on "interactive digital extensions of human abilities". More specifically, the authors

102 define the research field of human augmentation as addressing methods, technologies, and their

103 applications for enhancing a human's sensing, action, or cognitive abilities. This is achieved through

104 sensing and actuation technologies, fusion and fission of information, and AI methods (Raisamo et al.,

105 2019).

106   A related but different term is "human enhancement", which is the broader field of utilizing natural

107 or artificial means to improve human beings or human skills (Villa, Niess, Nakao, et al., 2023), by

108 overcoming the current limitations of the human body (Raisamo et al., 2019). For instance, certain

109 medications, surgeries, and genetic enhancement would fall under the umbrella of human enhancement.

110 As a result, in the context of this paper, HATs are defined as near-body, interactive technologies that aim to

111 directly enhance users' motor, sensory, and cognitive abilities.

112 **1.1.2. Cognitive Augmentation** Cognitive augmentation (i.e., augmented cognition (Fuchs et al., 2007;

113 Reeder et al., 2017; Stanney et al., 2009)) refers to the use of HATs to enhance human cognitive

114 abilities (Raisamo et al., 2019). This includes improving acquiring or generating knowledge and

115 understanding of the world around us, for example, enhancing users' attention, memory, reasoning,

116 problem-solving, or decision-making (Cinel et al., 2019). Prior research in cognitive augmentation has, for

117 example, focused on memory augmentation using lifelogging (Dingler et al., 2016, 2021; Sellen et al.,

118 2007) or neurofeedback training in VR (Accoto et al., 2021). Further research examples include

119 smartwatches for health-related decision making (Reeder et al., 2017) and an "affective umbrella"

120 wearable for emotion regulation (K. Chen et al., 2023).

121   Cognitive augmentation may utilize neuroscience technologies to record and act on brain activity.

122 The most popular non-invasive neuroscience technologies to record brain activity are EEG, functional

123 near-infrared spectroscopy, functional magnetic resonance imaging, and magnetoencephalography

124 (see Cinel et al. (2019) for a review). To stimulate brain activity, common non-invasive technologies include

125 transcranial electrical stimulation, transcranial magnetic stimulation, and focused ultrasound (Cinel et al.,

126 2019). Only in the medical field, invasive methods such as deep brain stimulation to treat movement and

127 memory impairments and electrodes implanted in the brain (to treat epilepsy) are frequently used (Cinel

128 et al., 2019). In their review of neurotechnologies in the area of cognitive augmentation, Cinel et al. (2019)

129 highlight the importance of tracking the ethical issues and implications of these technologies. One of those

130 issues is the user's sense of agency (Cinel et al., 2019), which we define in the next section.

131
132

> **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).

133 **1.1.3. Sense of Agency** The sense of agency refers to the experience of controlling one's actions and

134 their consequences (Limerick et al., 2014; Moore, 2016), allowing us to recognize ourselves as the agent

135 of our behavior (Jeannerod, 2003).

136   HCI and cognitive neuroscience try to understand how people experience agency (Bennett et al.,

137 2023; Limerick et al., 2014). For that, measures of agency have been constructed. Commonly, it is

138 assessed with direct measures that explicitly ask participants to rate their subjective sense of agency with

139 Likert scales on self-report questionnaires such as the *Sense of Agency Scale* (Tapal et al., 2017) or

140 customized scales. Indirect measures of agency have also been proposed. Haggard et al. (2002)

141 introduced the "intentional binding effect" as an implicit measure of agency, which refers to a subjective

142 compression of time between a voluntary action and its sensory consequence. This perceived time

143 interval can be assessed with the Libet clock method (Libet et al., 1993) or interval estimation (Engbert

144 et al., 2007).

145   In neuroscience, researchers also investigate objective, physiological measures of agency.

146 Through human brain imaging, distributed networks related to agency can be studied (Wolpe & Rowe,

147 2014). Neurophysiological indicators have been shown to correlate with the sense of agency, enabling the

148 continuous measurement of agency in real-time using EEG data (Jeunet et al., 2018; Kang et al., 2015).

149 Specifically, Kang et al. (2015) found that EEG alpha band activity, which is an important neural metric for

150 information processing (Klimesch, 2012), to be the main neural oscillation of the sense of agency,

151 suggesting the brain's anterior frontal lobe as an important area for generating agency. Further studies

152 found that the sense of agency correlates with increased alpha and beta EEG power in the

153 parieto-occipital regions, indicating that brain activity reflects changes in the sense of agency during hand

154 movement with delayed visual feedback (Bu-Omer et al., 2021). Another study using dual EEG setups in a

155 dyadic context of role switching during imitation highlighted the role of alpha and beta frequency bands in

156 distinguishing between self- and other-ascription of action primacy, showing the complex neural dynamics

157 of agency in interactive settings (Dumas et al., 2012).

158   Beta frequency, similar to alpha frequency, is also significant in understanding the sense of

159 agency. The modulation of local population activity and changes in functional connectivity, mediated by the

160 beta band, indicate a network perspective of the sense of agency. One study found that during the belief of

161 agency, the primary motor cortex (M1) shows stronger functional connectivity, mediated by the beta band,

162 to the inferior parietal lobe and right middle temporal gyrus, suggesting a network supporting the sense of

163 agency based on different causal beliefs (Buchholz et al., 2019).

164   For example, neurotechnologies intervene between the user's intention and action and hence

165 seem capable of altering human's sense of agency (Goering et al., 2021). For example, previous work by

166 Haselager (2013) found that Brain-Computer Interfaces (BCIs) may disrupt the sense of agency, leading

167 users to doubt their role in actions, concluding that awareness of this problem will help to solve it.

168
> **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).

169

2.   Literature Review

171   This scientific background shows that the HCI community must be aware of users' potential loss of

172 agency in human augmentation. We begin with a literature review to understand the sense of agency for

173 HATs in the context of HCI. Several areas of augmentation often overlap in their implementation and

Figure 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.*
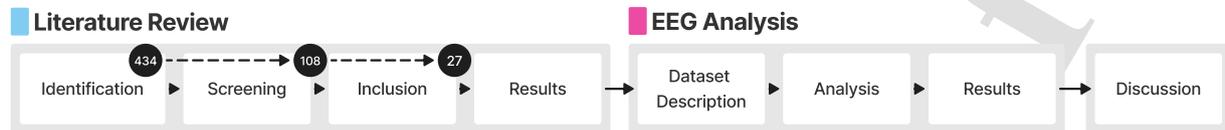
174 practical approaches (Raisamo et al., 2019), providing transferable methodologies and frameworks that

175 enhance the study of cognitive augmentation. Our paper aims to foster a holistic understanding of

176 augmentation within HCI, emphasizing how lessons from motor and sensory domains can support and

177 inform advancements in cognitive augmentation; thus, this literature review focuses on agency in cognitive

178 augmentations but extends and draws insights from motor and sensory augmentations as part of the

179 ecosystem of human augmentation technologies (Raisamo et al., 2019). We performed a systematic

180 literature review following the guidelines from the Preferred Reporting Items for Systematic Reviews and

181 Meta-analyses (PRISMA) (Page et al., 2021). The following sections describe the review's search strategy

182 and selection process, experimental design, and conclusions.

183 **2.1.   Search Strategy**

184   The ACM Digital Library and IEEE Xplore electronic databases were searched for primary HCI

185 studies on cognitive augmentation, which also measure or consider the sense of agency. On the ACM

186 Digital Library, the content type "Research Articles" was selected. On IEEE Xplore, publications were

187 filtered for "Journals" and "Conferences". We considered records from 2003 to 2023 to focus on studies

188 where cognitive augmentation technologies gained popularity. To allow for the reproducibility of search

189 results, the exact search queries can be found in the Appendix in Table 1. After testing various keywords

190 and combinations, we ultimately selected one specific search query that combined the terms "sense of

191 agency" with "cognitive augmentation", "augmented cognition", or "human augmentation", allowing us to

192 obtain articles that use the established terms. Additionally, since human augmentation is not a well-defined

193 term yet, we decided also to include a more descriptive query (see Query 2 in Table 1) which combined: (i)

194 "sense of agency", (ii) "augment*" or several synonyms, (iii) "cogniti*" or "brain", and (iv) "human-computer

195 interaction", aiming to capture all relevant HCI articles, even if they do not mention the term

196 "augmentation". The "human-computer interaction" keyword was added to filter out records that lacked

197 relevance to HCI research, as, without this addition, the volume of records was not manageable within our

198 time constraints.

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

199   Through this search process, a total of 445 records were identified from the ACM Digital Library (n

200 = 378) and IEEE Xplore (n = 67). Eight duplicate records were removed, which were caused by utilizing

201 the two different search queries. Three records had to be removed because they were not research

202 articles. In total, this resulted in 434 publications to be screened.

203   We focused our search on the ACM Digital Library and IEEE Xplore because these two databases

204 comprehensively cover the main venues where peer-reviewed HCI and human augmentation research is

205 typically published (e.g., CHI, UIST, TEI, IEEE VR, and related conferences and journals). While we

206 recognize that additional databases (e.g., Web of Science, Scopus) might contain relevant work, our

207 priority was to capture studies from the largest HCI-focused repositories. Moreover, preliminary exploration

208 suggested that most primary HCI research on augmentation appears in these core platforms. Future

209 reviews could expand beyond these databases to capture a broader range of interdisciplinary research,

210 but for this work, we aimed to ensure depth and relevance within the HCI context .

211 **2.2. Selection Criteria and Process**

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

213 1. Peer-reviewed, original work (excluding literature reviews)

214 2. Written in English

215 3. Sense of agency measured or considered

216   4. Focus on cognitive augmentation (i.e., HATs that aim to enhance cognition)

217   We included both quantitative and qualitative research and imported all records into

218 Citavi (Software, 2020-10-29), version 6.7, to document databases and search queries. Although a single

219 author conducted the initial screening and selection, decisions and exclusion reasons were recorded

220 systematically, and any ambiguous cases were reviewed in consultation with another author to reduce

221 potential bias.

222   The screening process (see Figure 2) involved three phases: Identification, Screening, and

223 Inclusion. In the first phase, we reviewed titles and abstracts, excluding 326 records. Unclear cases

224 advanced to the second phase.

225   In the second phase, we reviewed the full texts of the remaining 108 publications, discarding those

226 that failed to meet the inclusion criteria. However, following the described process, we found zero

227 publications that met all initial inclusion criteria, as none of the studies specifically focused on cognitive

228 augmentation.

229   Consequently, we extended inclusion criterion four to: "Focus on human augmentation or related

230 domains from which insights on agency can potentially be transferred to cognitive augmentation."

231 Following this change, we systematically re-screened the same 108 publications, applying the same

232 stepwise procedure and documentation protocol used in the initial screening. In particular, the single

233 reviewer again recorded the reasons for inclusion or exclusion, and any ambiguous cases were discussed

234 with a second authoring order to ensure the re-screening process remained as rigorous and transparent as

235 our initial review steps. As a result, we included 27 works in this review (see exclusion reasons in Figure 2).

236 **2.3.   Results**

237   In the following, we report the analysis of the 27 reviewed studies. We grouped them into cognitive,

238 motor, and sensory augmentation topics based on the framework by Raisamo et al. (2019). Further studies

239 that did not fall under these three categories, however, address agency in a context related to human

240 augmentation, are presented in the *Agency in related domains* section (see Table 2 for an overview).

241 **2.3.1.   Agency in Motor Augmentation** Seven articles were identified that examine agency related to

242 motor augmentation (Coyle et al., 2012; Kasahara et al., 2019, 2021; Shahu et al., 2022; Tajima et al.,

243 2022; Venot et al., 2022).

244   Kasahara et al. (2019) developed a preemptive force-feedback system using electrical muscle

245 stimulation (EMS) to enhance reaction time while maintaining the user's sense of agency. Their

246 preemptive action approach with optimal timing (here, a tapping task with EMS actuation 160 ms after the

247 visual target) yielded faster reaction times than participants' own reaction times and a higher sense of

Figure 2
PRISMA flow diagram of the literature review process. Adapted from (Page et al., 2021).
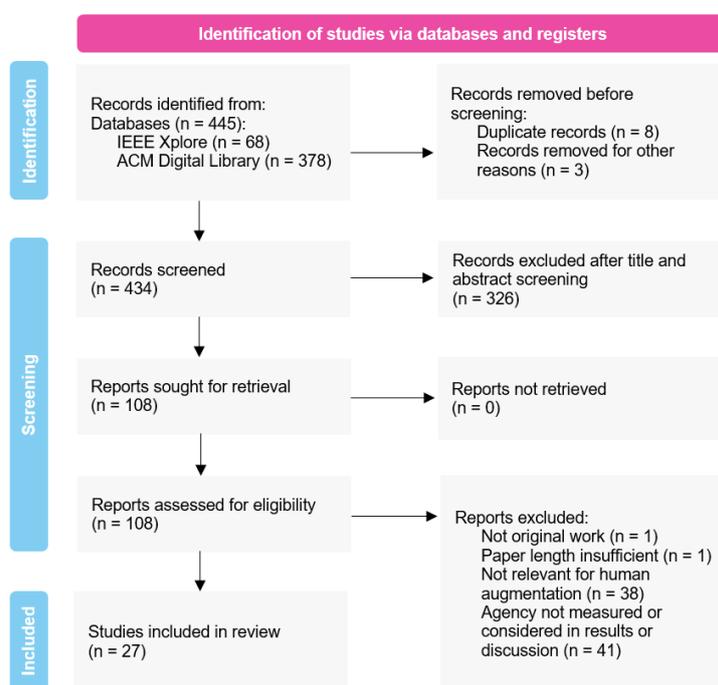
248 agency than traditional EMS methods, though voluntary actions still provided the highest sense of

249 agency (Kasahara et al., 2019). Kasahara et al. (2021) extended their research with a reaction time

250 experiment under three EMS conditions. Faster reaction times were retained post-EMS removal only when

251 participants trained with optimal timing of preemptive action, suggesting that preserving agency improves

252 motor adaptation after EMS training.

253   Yet, Kasahara et al. (2019) only considered scenarios of congruent situations when an alignment

254 between user-driven and machine-driven touch exists. Given this limitation, Tajima et al. (2022) expanded

255 upon this work by comparing assistive-touch and adversarial-touch in a force-feedback EMS study. They

256 found that participants reported a higher sense of agency for favorable outcomes (assistive-touch) as

257 compared to unfavorable outcomes (adversarial-touch). This suggests that the level of perceived agency is

258 affected by an outcome bias. They also created the "agency-assistance trade-off matrix" (see Figure 3),

259 depicting design implications for haptic systems using actuators. Joint success (i.e., user and EMS

260 correct) preserves some sense of agency even with faster computer-driven touch, replicating previous

261 studies (Kasahara et al., 2019, 2021). Forced success (i.e., user incorrect, EMS correct) involves

262 corrective haptic assistance where the user involuntarily performs the correct action due to faster

263 computer-driven touch, which hinders agency. Forced failure (i.e., user correct, EMS incorrect) should be

264 prevented as it results in an incongruent as well as false outcome, whilst also diminishing agency. Joint

Table 2

Overview of literature included in review

Section	Reference
Agency in cognitive augmentation	(Semertzidis et al., 2023)
Agency in motor augmentation	(Coyle et al., 2012) (Kasahara et al., 2019, 2021) (Tajima et al., 2022) (Shahu et al., 2022) (Venot et al., 2022)
Agency in sensory augmentation	(Zolyomi & Snyder, 2020)
Agency in related domains *- Neurotechnology*	(Martinez et al., 2022) (Hougaard et al., 2022; Hougaard et al., 2021) (Mercado-García et al., 2021)
- Human-computer integration	(Mueller et al., 2023)
- VR and AR	(Gauthier et al., 2021) (Zhang et al., 2022) (Jun et al., 2018) (Seinfeld et al., 2022) (Takada et al., 2022) (Miura et al., 2021) (W. Sun et al., 2022a, 2022b)
- AI and machine learning applications	(Xu et al., 2023) (Wang et al., 2022) (Thieme et al., 2023) (Sali et al., 2012) (Y. Sun et al., 2023) (Ahmad et al., 2022)

265 failure (i.e., user and EMS incorrect) results in a negative outcome but could be useful for adversarial

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

267   Shahu et al. (2022) examined EMS acceptance in four scenarios (motor learning, virtual reality,

268 media player, and road safety), where one of the investigated factors was controllability (i.e., "a user's

269 capacity to control a situation (sometimes referred to as 'sense of agency')" (Shahu et al., 2022)). An

270 online survey and interviews showed the highest acceptance for VR-EMS and the lowest for road safety,

271 where loss of control was a negative factor. They recommend EMS systems maintain user control and

272 offer alternatives to preserve the sense of agency. Finally, Coyle et al. (2012) studied the impact of

273 assistance levels (none/mild/medium/high) on agency in a machine-assisted point-and-click task with a

274 gravity algorithm enhancing users' mouse movement. They found the highest sense of agency in

275 no-assistance and mild-assistance conditions, with no significant difference between these two levels,

276 indicating that computer assistance up to a certain level can still allow a high sense of agency. However,

277 medium and high assistance significantly reduced agency. These findings suggest that assistance can

Figure 3
Agency-assistance trade-off matrix. Adapted from (Tajima et al., 2022).
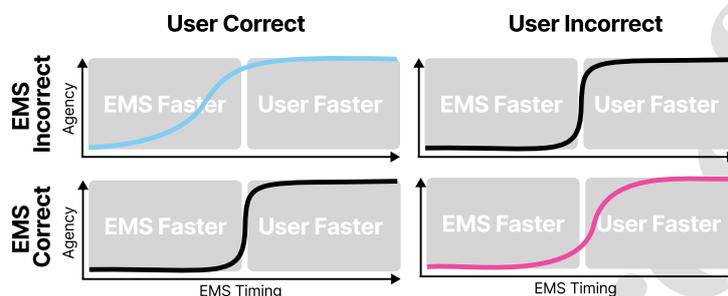
278 lead to a loss of agency once a certain threshold is reached, which is relevant for human augmentation

279 applications. So far, most identified studies on motor augmentation have focused on EMS technology.

280 Venot et al. (2022) investigated a multimodal BCI, examining how the timing of motor imagery tasks

281 affected performance. Their BCI integrated eye-tracking to enhance the overall sense of agency, which

282 participants reported via a questionnaire. However, the authors did not report or discuss the agency

283 results. In summary, these motor augmentation studies emphasize that the level of assistance and timing

284 of the intervention are relevant factors for maintaining a sense of agency.

285 **2.3.2.   Agency in Sensory Augmentation** Research by Zolyomi and Snyder (2020) relates to sensory

286 augmentation due to its focus on vision-enhancing technology. It is centered on understanding the social

287 implications of digitally enhanced vision based on a head-mounted assistive device for low vision. In

288 interviews with long-term users, the authors observed that users' desire to experiment with the assistive

289 technology and their perception of its value was influenced by users' overall sense of agency in

290 life (Zolyomi & Snyder, 2020). For future research on agency in cognitive augmentation, this suggests that

291 considering a more holistic view of agency in life, rather than just during specific machine-assisted tasks,

292 may lead to valuable insights.

293 **2.3.3.   Agency in Related Domains** In the following, we analyze the role of agency in domains related to

294 human augmentation, grouped by (i) neurotechnology, (ii) human-computer integration, (iii) VR and AR,

295 and (iv) AI and machine learning applications.

296   **Neurotechnology** Neuroscience technology is commonly used to enhance human cognitive

297 abilities (see subsubsection 1.1.2). (Cinel et al., 2019). Therefore, studies that do not investigate

298 neurotechnology specifically for human augmentation but consider the role of agency is relevant here, as

299 insights can likely be transferred to the design of cognitive HATs. A mixed-method study by Martinez et al.

300 (2022) examined the ethical concerns for neurotechnology in the future workplace. Participants had

301 generally positive attitudes towards future brain-scanning technologies, especially those boosting

302 concentration (an example of cognitive augmentation). However, interviews revealed concerns about "trust

303 and agency," particularly regarding devices that alter emotional states, which the authors suggest threaten

304 users' sense of agency (Martinez et al., 2022). In the context of BCIs for stroke rehabilitation, low BCI

305 performance can decrease agency (Hougaard et al., 2021). Hougaard et al. (2021) found that fabricated

306 input (i.e., preprogrammed positive feedback) increased perceived agency and reduced frustration in users

307 in (i) a surrogate BCI based on eye blinks (Hougaard et al., 2021), (ii) a surrogate BCI study with stroke

308 patients (Hougaard et al., 2022), and (iii) real motor imagery tasks in an online BCI study (healthy

309 participants) (Hougaard et al., 2022).

310   Mercado-García et al. (2021) investigated whether the design approach impacts the modulation of

311 EEG brain signals in a motor imagery task. They found that user-centered design (including a VR CAVE

312 system) enhanced brain activity modulation compared to traditional Graz BCI design. The authors suggest

313 that natural interactions that resemble BCI users' daily life activities offer them "a real sense of

314 agency" (Mercado-García et al., 2021). However, users' agency was not measured, hence the benefit on

315 agency is an assumption that needs further investigation.

316   **Human-Computer Integration** According to Raisamo et al. (2019), human-computer integration,

317 which uses computing resources and AI to support and work together with a human, is closely connected

318 to cognitive augmentation. Hence, insights into agency in human-computer integration can likely inform

319 cognitive augmentation research. Mueller et al. (2023) explored shared agency of bodily control in

320 intertwined human-computer integration, using the "EduExo" exoskeleton with an electromyography sensor

321 to support arm movement (i.e., motor augmentation). The user can access all system data on a laptop,

322 making the machine's agency transparent. The authors present a framework with two key dimensions of

323 intertwined systems (awareness and alignment of the machine's agency) and four system roles (angel,

324 butler, influencer, adversary) (Mueller et al., 2023). Their framework supports designing cognitive

325 augmentation systems with shared agency.

326   **VR and AR** Human augmentation builds upon and draws elements from the fields of VR and

327 AR (Raisamo et al., 2019). Therefore, examining the sense of agency in those contexts can be insightful

328 for designing cognitive augmentation technologies.

329   Several identified VR studies that consider the sense of agency focus on embodiment (Gauthier

330 et al., 2021; Jun et al., 2018; Miura et al., 2021; Seinfeld et al., 2022; Takada et al., 2022; Zhang et al.,

331 2022). It was shown that embodying a body-matched virtual avatar as opposed to a virtual object

332 increased participants' sense of agency during a cognitive task (Gauthier et al., 2021). Furthermore,

333 avatar hand realism affected agency, with lower agency scores found for abstract hands compared to

334 iconic or realistic hands (Zhang et al., 2022). Body continuity (i.e., whether the virtual hands and arms

335 were disconnected or connected) showed no significant effect on perceived agency (Zhang et al., 2022). A

336 VR study on the emotional effects of the full-body ownership illusion demonstrated that movement

337 synchrony between virtual and real body led to increased emotional valence as well as increased sense of

338 agency compared to a pre-recorded movement condition(Jun et al., 2018). Another VR study, in which

339 motor tasks were performed, found that participants' sense of agency was higher in a virtual hand

340 condition compared to a physical keyboard condition (without virtual representation) (Seinfeld et al., 2022).

341 However, there was no significant difference in agency between virtual hands and virtual

342 controllers (Seinfeld et al., 2022). In VR, it is also possible to embody multiple bodies simultaneously. In a

343 "Parallel Embodiment" system developed by Takada et al. (2022), users play ping-pong while

344 simultaneously controlling two robot arms. In a survey, users reported high ratings for the sense of agency

345 over both robot arms despite visuomotor incongruences. However, some users suggested the robot arm

346 itself had agency, with comments such as "the robot arm is moving on its own" (Takada et al., 2022).

347 Takada et al. (2022) conclude that agency may be influenced by users' prior knowledge of another agent's

348 presence. Furthermore, Miura et al. (2021) found that participants perceived agency over four virtual

349 bodies in parallel when controlling them simultaneously. The results further suggest that self-reported

350 agency might have decreased with more bodies. In the context of object translation in handheld AR,

351 W. Sun et al. (2022b) observed a higher subjective and objective agency in one degree of freedom

352 compared to three degrees of freedom. W. Sun et al. (2022a) also revealed a negative association

353 between mental workload and agency in head-mounted AR.

354   **AI and Machine Learning Applications** AI methods are an essential part of human

355 augmentation (Raisamo et al., 2019), including memory augmentation (Dingler et al., 2021). For instance,

356 AI assistants can efficiently carry out various tasks and make decisions for the user on their behalf. The

357 model by Raisamo et al. (2019) for wearable augmentation proposes that AI is an enabling technology

358 specifically for cognitive augmentation. Hence, the role of agency in AI and machine learning (ML)

359 applications will be considered in the following since insights apply to cognitive augmentation. Xu et al.

360 (2023) investigated explainable AI (XAI) in AR, proposing an XAI design framework based on a survey and

361 expert workshops. To provide user agency, they recommend always making AI explanations accessible

362 and offering detailed explanations upon request. In AI-mediated social interactions, Wang et al. (2022)

363 developed an AI agent for online learning platforms assisting users in building social connections. An

364 interview study revealed that students were concerned about losing agency over the connections they

365 built. The authors suggest that a balance is required between ensuring successful interactions mediated

366 by AI and preserving users' agency with whom to start a conversation. This aligns with findings from motor

367 augmentation on the trade-off between assistance and agency (Coyle et al., 2012) (see

368   subsubsection 2.3.1). In healthcare, Thieme et al. (2023) developed an AI application to predict treatment

369   outcomes in human-supported, internet-delivered Cognitive Behavioral Therapy (iCBT) for depression and

370   anxiety. They found that AI design could affect clinical supporters' sense of agency and recommend that

371   AI should inform the care rather than interfere with medical assessments, keeping the supporter in charge

372   of examining patients' individual circumstances and potential reasons for the AI prediction outcome. Sali

373   et al. (2012) explored natural language understanding (NLU) in games, finding that players reported more

374   agency when the NLU interface provided pauses and prompts (as opposed to free-form text entry and

375   reactive pauses), even if it limited their actions and free will. This suggests that guided actions can

376   enhance the sense of agency. Moreover, Y. Sun et al. (2023) found that users of automated machine

377   learning systems actively exercise agency to overcome challenges in customizability, transparency, and

378   privacy by employing workaround strategies. Finally, Ahmad et al. (2022) found that tangible controls, like

379   hardware buttons, improve users' agency over smart voice assistants and their privacy. These insights

380   could benefit cognitive HATs, such as voice-assisted memory extenders.

381   **2.3.4.   Agency in Cognitive Augmentation: A Research Gap** The systematic literature search

382   identified no study that directly aimed at enhancing human cognitive capabilities (such as memory,

383   problem-solving, attention, cognitive overload, etc.) using digital technology while also measuring or

384   discussing the sense of agency. This research gap will be addressed in the discussion (see

385   subsection 4.3). One identified study closely related to cognitive augmentation was conducted by

386   Semertzidis et al. (2023), who developed Dozer, a closed-loop wearable beanie that accelerates sleep

387   onset through auditory and electrical brain stimulation. After an EEG detects drowsiness, the user's brain

388   is stimulated through transcranial alternating current stimulation (tACS), and speakers play pink noise for

389   sleep enhancement. In an in-the-wild study, the authors identified "closed-loop neurocentric

390   agency" (Semertzidis et al., 2023) as a user experience theme related to bodily agency. The authors found

391   that: (i) participants demonstrated high agency over the system despite feeling disconnected due to a lack

392   of feedback, process understanding, and system familiarity. (ii) Knowledge of the system's function is

393   important for experiencing agency. (iii) Bodily-integrated systems can provide a high sense of agency

394   without explicit user inputs (i.e., initiating causal influence over the system). Nevertheless, participants

395   reported a diminished sense of body ownership and high awareness of the system's hardware, which

396   compromised Dozer's ability to promote sleep onset effectively. Whilst aiming to accelerate sleep onset

397   does not directly enhance cognitive capabilities, Dozer can be considered a cognitive augmentation

398   technology in a broader sense. It targets cognitive processes involved in sleep regulation through a

399   closed-loop wearable utilizing EEG, auditory, and electrical brain stimulation, thereby augmenting cognitive

400 aspects related to sleep onset. Overall, this study implies that the user's understanding of the HAT's

401 functionality may be relevant for maintaining a sense of agency. Yet, the specific field of sense of agency in

402 cognitive augmentation remains largely unexplored.

2.4. Mapping the Literature on Agency on Cognitive Augmentation

404 Our literature review shows a research gap concerning the role of agency in cognitive

405 augmentation technologies. This gap might reflect a underexploration of the topic within the HCI

406 community, as existing publications have overlooked the real-time quantification of cognitive agency due to

407 traditional focus areas or the limitations of our search to two databases[1]. While studies on agency in motor

408 augmentation are relatively more prevalent (cf. (Coyle et al., 2012; Kasahara et al., 2019, 2021; Shahu

409 et al., 2022; Tajima et al., 2022; Venot et al., 2022)), our findings suggest a notable disparity. Agency has

410 been predominantly associated with motor control, defined as the subjective experience of control over

411 one's *actions* (Moore, 2016). However, the concept of agency is equally important in cognitive

412 augmentation. A diminished sense of cognitive agency can result in adverse outcomes, such as a

413 dangerous shift in responsibility to the cognitive HAT (Friedman & Kahn, 1992) or increased risk-taking

414 behavior (Villa, Kosch, et al., 2023). Addressing this gap is important for designing cognitive augmentation

415 systems that appropriately balance human and technological control.

416 To advance understanding in this area, we leverage EEG data as an objective measure to

417 investigate subjectively perceived cognitive agency. EEG provides a unique advantage by capturing

418 real-time neural activity throughout an experiment, enabling continuous, objective agency measures. This

419 contrasts with traditional questionnaires, which collect subjective, retrospective data and are limited to

420 specific moments in the experimental process. Building on the EEG study by Villa, Kosch, et al. (2023),

421 which explored the influence of external cues on causal beliefs in a risk-taking task, we focus specifically

422 on how EEG-based neural correlates reflect cognitive agency. Participants in this study believed they were

423 performing the task independently or with AI assistance, allowing us to manipulate their perceived sense of

424 agency regarding perceived sense of agency. EEG has proven an efficient measure for assessing

425 agency (Buchholz et al., 2019; Bu-Omer et al., 2021; Dumas et al., 2012; Kang et al., 2015), making it an

426 ideal tool for estimating the perceived level of agency in real-time. Our analysis meets and exceeds

427 recommended sample sizes by leveraging the open dataset by Villa, Kosch, et al. (2023) consisting of 27

428 participants completing 1080 trials. Trial counts for EEG research to ensure statistical power and reliable

429 data quality (Boudewyn et al., 2018; Melnik et al., 2017). The re-analysis aimed to estimate if the sense of

430 agency can be assessed in real-time when using cognitive augmentation technologies. This work

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[1] ACM Digital Library and IEEE Xplore.

431 highlights the relevance of EEG in agency research and lays the groundwork for designing cognitive HATs

432 that prioritize the user's cognitive autonomy and responsibility.

3.   Research Model: Assessing the Impact of Perceived AI Support on Sense of Agency

435   While the impact of technology on perceived agency attracted attention in HCI (Bennett et al.,

436 2023; Cornelio et al., 2022; Coyle et al., 2012; Limerick et al., 2014), quantifying and understanding

437 perceived cognitive agency remains a significant research gap. Our literature review indicates that neural

438 activity is strongly linked to the perception of agency. Prior research has successfully utilized EEG to

439 quantify agency perception, demonstrating that specific neural features serve as reliable indicators. For

440 example, Kang et al. (2015) showed that alpha and beta band frequencies in the EEG are closely

441 associated with the perception of agency. In their work, alpha and beta frequencies have been effectively

442 used to capture variations in self-attributed actions, suggesting them as quantifiable real-time metrics for

443 perceived agency in the study of agency. More importantly, research further demonstrates that these

444 neural markers correlate with the subjective sense of agency (Yun et al., 2019). This section describes the

445 data analysis of an EEG experiment that evaluated the perceived cognitive agency. In the following, we

446 used an open dataset provided by Villa, Kosch, et al. (2023) to evaluate the feasibility of EEG data for

447 assessing cognitive agency. While EEG has been extensively validated for motor agency through markers

448 like Event-Related Potentials (ERPs) (Luck, 2014), the application of EEG to cognitive agency is less

449 established, with potential overlaps between neural patterns of agency and those of attention or working

450 memory (Bu-Omer et al., 2021; Kang et al., 2015). Despite these challenges, emerging evidence

451 demonstrates that EEG can reliably capture neural correlates of cognitive agency, such as parieto-occipital

452 alpha suppression and frontal theta activity, during decision-making and attribution tasks (Buchholz et al.,

453 2019; Kang et al., 2015). Recent studies further suggest that EEG can differentiate self-generated from

454 externally guided cognitive processes, including those involving AI assistance (Villa, Kosch, et al., 2023).

455 To enhance reliability and applicability, future research should employ controlled experimental paradigms

456 that isolate cognitive agency, address EEG's practical challenges through robust noise reduction and trial

457 design, and triangulate results using complementary behavioral and subjective methods (Kirwan et al.,

458 2023). By addressing these considerations, we evaluate EEG as a tool to measure cognitive agency, as

459 previous research has used it to assess sensory and motor agency.

460   To achieve this goal, we analyzed an EEG experiment with 27 participants to understand the

461 impact with and without perceived AI assistance (Villa, Kosch, et al., 2023) on cognitive agency (see

462 Figure 1). Although previous work showed that EEG is a validated and reliable measure for studying the

463 sense of agency in motor augmentation (Bu-Omer et al., 2021; Dumas et al., 2012; Kang et al., 2015),

464 EEG has not yet been extensively evaluated in the context of cognitive augmentation. Thus, the analysis

465 investigates how EEG metrics, such as alpha and beta band activity, could form an alternative metric for

466 quantifying agency in interactive systems.

467 **3.1. Experimental Design**

468   The original study employed a within-subjects lab design focusing on one variable of interest: the

469 verbal system description (DESCRIPTION). In the AI-ASSISTANCE condition, participants were told the

470 system augmented cognitive skills, while in the NO-ASSISTANCE condition, no augmentation was claimed.

471 Additionally, CCT (Columbia Card Task) task-related variables were collected: (1) LOSS CARDS (one vs.

472 three loss cards), (2) WIN AMOUNT (10 vs. 30 points), and (3) LOSS AMOUNT (250 vs. 750 points). Verbal

473 descriptions were counterbalanced, and CCT variables were randomized.

474 **3.2. Dataset Choice**

475   The dataset provided by Villa, Kosch, et al. (2023) is well-suited for investigating changes in

476 cognitive agency for several reasons. First, the experimental design in the dataset explicitly manipulated

477 participants' expectations through verbal system descriptions, which prior research has shown to influence

478 the sense of agency (Buchholz et al., 2019). The verbal manipulation allows for a systematic assessment

479 of agency-related shifts, providing a foundation for analyzing neural correlates of agency. Second,

480 extensive research demonstrates that EEG metrics, particularly oscillatory activity in the alpha and beta

481 frequency bands, are reliable real-time markers for sensing changes in perceived cognitive agency. For

482 example, studies have shown that alpha-band activity is associated with self-referential processing, an

483 essential component of perceived agency (Yun et al., 2019). At the same time, beta-band oscillations

484 reflect motor and cognitive processes underlying intentional control (Kang et al., 2015). Furthermore,

485 neurophysiological evidence supports the relationship between EEG changes and agency perception

486 across diverse contexts, including cognitive tasks. Our analysis bridges the gap for evaluating changes for

487 the agency during cognitive augmentation through corresponding cortical activity using the existing

488 experimental setup and EEG metrics from this dataset.

489 **3.3. Task Description**

490   Participants played the Columbia Card Task (CCT) game according to Figner et al. (2009). The

491 CCT is a card game where players can win or lose points by flipping cards. Depending if the player flips a

492 win or loss card, the player wins or loses points. The number of points influences the CCT a participant

493 can win (i.e., 10 and 30 for win cards) or lose (i.e., 250 and 750 for loss cards). Players can flip another

494 win card if they have flipped a win card before. The game round ends when the player flips a loss card.

495 Overall, the participants played 20 rounds. At the start of each round, the cards were presented facing up

496 (visible to the participants), then flipped down and shuffled at high speed so the participants could not

497 follow them (Villa, Kosch, et al., 2023). The initial card placement is irrelevant as the game is manipulated:

498 in win rounds, participants flip win cards until loss cards appear at the end of the deck, while in loss

499 rounds, loss cards appear early.

500   **Verbal System Description.** Prior work suggests that external cues can influence causal beliefs

501 (self-attribution vs. external attribution), thereby modulating the sense of agency (Buchholz et al., 2019).

502 We used this finding by analyzing participants' causal attributions through system descriptions.

503 Specifically, participants were told to engage in the CCT task either in an AI-ASSISTANCE or the

504 NO-ASSISTANCE condition. In the AI-ASSISTANCE scenario, participants were informed that a BCI

505 monitored their brain activity and emitted inaudible binaural sounds (Colzato et al., 2017) to enhance

506 visual processing and improve card selection accuracy. The cover story highlighted the cognitive benefits

507 of these sounds, including their documented positive effects (Clements-Cortés et al., 2016). Importantly,

508 there was no active system in the practical implementation. In the NO-ASSISTANCE scenario (control

509 condition), participants were told the augmentation technology was inactive, making their performance

510 entirely reliant on their own skills in visualizing card movements and gameplay engagement.

3.4. Apparatus

512   Lab Streaming Layer (LSL) was used for time-series data capture, handling networking, time

513 synchronization, and recording EEG streams with signal annotations. Tasks were performed on a

514 Windows 10 desktop (HP Z1 G6, i7-10700 processor, 16 GB RAM) with a 27-inch monitor at 60 Hz. EEG

515 data were annotated for each button press, including card flips and game round advances. Participants

516 used a mouse to interact with the Columbia Card Task (CCT) while seated approximately 75 cm (29.5

517 inches) from the screen, adjusted to eye level.

3.5. Participants

519   Participants were recruited via university email lists and channels, excluding those with prior

520 knowledge of EEG or human augmentation systems to prevent bias. Of 30 recruited individuals, one

521 declined data use post-experiment, and two were excluded for missing expectancy ratings, leaving 27

522 participants ($N = 27$, 17 males, 10 females, $M = 29.13$, $SD = 9.51$). They reported moderate technical

523 competence ($M = 4.76$, $SD = 1.43$). The study was approved by the German Psychological Society

524 (DGPs) and the local ethics board (ID: EK-MIS-2020-023).

3.6. Experimental Procedure

525
526 Participants were randomly assigned to either the AI-ASSISTANCE or NO-ASSISTANCE condition
527 with balanced distribution. After a briefing on objectives and privacy measures, informed consent was
528 obtained per the Declaration of Helsinki. Participants provided demographic data, rated technical
529 proficiency on a seven-point Likert scale, and were introduced to human and cognitive augmentation
530 concepts and equipment. Depending on their condition, they received a system overview and answered
531 three comprehension questions. The CCT compensation model (0–10 euros based on performance) was
532 explained, though all participants ultimately received the maximum compensation. Training included
533 interface tutorials and loss scenario practice. An auditory threshold task was conducted to strengthen the
534 association of causal beliefs, with participants either notified about the augmentation's inactivity or
535 anticipating the system's (non-existent) sound output. Card selections and EEG data were collected during
536 CCT sessions with counterbalanced conditions. After each session, the perceived performance
537 improvements were assessed. Upon completion, they evaluated the augmentation system's usability,
538 measured belief in the system functionality, provided a full debrief, and sought consent for data usage,
539 ensuring compensation was not dependent on their decision.

3.7. Measurements

540
541 Previous work by Kang et al. (2015) has shown that Agency can be operationalized through alpha
542 (8 - 12 Hz) and beta (12 - 15Hz) band oscillations during motor tasks. In this analysis, we further test if this
543 operationalization holds for cognitive agency; *therefore, we study cognitive agency by evaluating the*
544 *spectral behavior of the alpha and beta bands for objectively assessing perceived agency in real-time.*

3.8. EEG Recording and Preprocessing

545
546 The authors collected EEG data at a sampling rate of 500 Hz using a LiveAmp amplifier (Brain
547 Products, Germany) equipped with 32 water-based electrodes arranged according to the International
548 10-20 layout on an R-Net elastic cap. The electrode positions were as follows: Fp1, F3, F7, F9, FC5, FC1,
549 C3, T7, CP5, CP1, Pz, P3, P7, P9, O1, Oz, O2, P10, P8, P4, CP2, CP6, T8, C4, FC2, FC6, F10, F8, F4,
550 Fp2, and Fz. Impedance levels were maintained below or equal to 20 kΩ, with FCz serving as the
551 reference electrode and FPz as the ground. Time synchronization was achieved using the Lab Streaming
552 Layer [2] framework while preprocessing and analysis were conducted using the MNE-Python Toolbox
553 (Gramfort et al., 2013). The authors applied a notch filter at 50 Hz and band-pass filtering between 1-30
554 Hz to eliminate high and low-frequency noise. The data was then re-referenced to the common average
555 reference (CAR). We performed artifact detection and correction using an Independent Component

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[2] https://labstreaminglayer.org

556 Analysis (ICA) with the extended Infomax algorithm (Lee et al., 1999) to mitigate the impact of attentional

557 shifts, cognitive load, and fatigue. The labeling and rejection of ICA components were automated using the

558 'ICLabel' plugin within MNE (Pion-Tonachini et al., 2019). The ICA-based preprocessing reduced artifacts

559 related to fatigue, movement, and attentional shifts.

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

# 4. Experimental Results

561   This section details our data analysis of the author's experimental study. We employed

562 independent-sample t-tests for questionnaire items to establish statistically significant differences between

563 the AI-assisted and no-assistance conditions. Conversely, we utilized generalized linear models (GLMs) to

564 analyze the Spectral Analysis values. This choice facilitated the dissociation of the effects arising from the

565 card type and those due to the experimental condition (AI-Assistance vs. No-Assistance). We first report

566 the assessment of belief in augmentation functionality, followed by perceived performance improvements

567 using a frequentist analysis as an alternative to the previously reported Bayesian analysis in Villa, Kosch,

568 et al. (2023), and finally, the EEG spectral analysis.

4.1. Post-Experiment Assessment of Belief in Augmentation

570   Following the experiment and debriefing of the conditions used in the study, participants indicated

571 their belief in the functionality of the augmentation system. Only 3.70% (1 out of 27) explicitly disbelieved

572 the system's capabilities. While 40.74% (11 out of 27) reported minor suspicions, the majority (51.85%, 14

573 participants) fully believed in the augmentation technology's effect. One participant (3.70%) did not

574 disclose their belief regarding the described functionality. The post-experimental perceived performance

575 improvement questions revealed that participants, on average, perceived the augmentation system as

576 facilitating task completion and enhancing performance and cognitive abilities. This perception further led

Figure 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.*
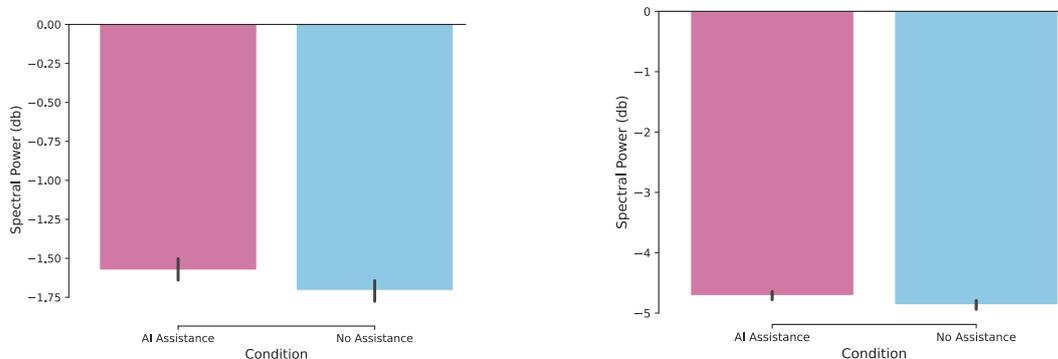
(a) *Alpha Band*   (b) *Beta Band*

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 Figure 5 and Figure 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. 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

598 NO-ASSISTANCE and Spectral Power, with an estimated coefficient of $-.15$ ($SE = .052$, $z = -2.98$, $p = .003$),

599 suggesting that Spectral Power decreased by $.15$ units when participants were informed that assistance

600 was not provided. Conversely, the 'Win Card' outcome was significantly associated with a reduction in

601 Spectral Power, evidenced by a coefficient of $-.95$ (SE = $.18$, $z = -5.30$, $p < .001$), indicating a substantial

602 decrease in Spectral Power associated with winning outcomes.

4.3. Discussion

604   In this section, we discuss and articulate the main findings of this paper, including mapping

605 neurophysiological markers of agency in motor tasks for cognitive augmentation, its impact on agency, and

606 future directions. For a broader overview of agency antecedents in HCI, see Bennett et al. (2023).

607 **4.3.1. Quantifying Sense of Agency in Cognitive Augmentations** The analysis study on cognitive

608 augmentation reveals how AI assistance affects users' sense of agency through its electrophysiological

609 data. Our findings reveal that participants experienced a significant decrease in the sense of agency when

610 led to believe in the presence of AI assistance, as evidenced by shared variations in alpha and low-beta

611 EEG power in the parieto-occipital regions. This suggests that the mere belief in AI assistance can

612 effectively lead to a diminished sense of agency in the context of cognitive augmentations at a

613 neurophysiological level.

614   Compared to a baseline condition (No-Assistance), this outcome was observed through

615 alterations in alpha and beta brain wave activities. Such findings highlight how perceived AI support can

616 evoke different patterns in brain frequency that can allow discrimination across agency states. The

617 decrease in the sense of agency aligns with the results reported by Bu-Omer et al. (2021), providing a

618 neurophysiological basis for understanding how external cues and perceived technological interventions

619 can modulate individuals' sense of control over their actions. This is in line with the call for disambiguating

620 agency definitions in HCI as outlined in Bennett et al. (2023).

621   The findings also reveal that winning outcomes lead to a significant decrease in spectral power

Figure 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.*

(a) *AI-Assistance.*   (b) *No-Assistance.*   (c) *AI-Assistance.*   (d) *No-Assistance*
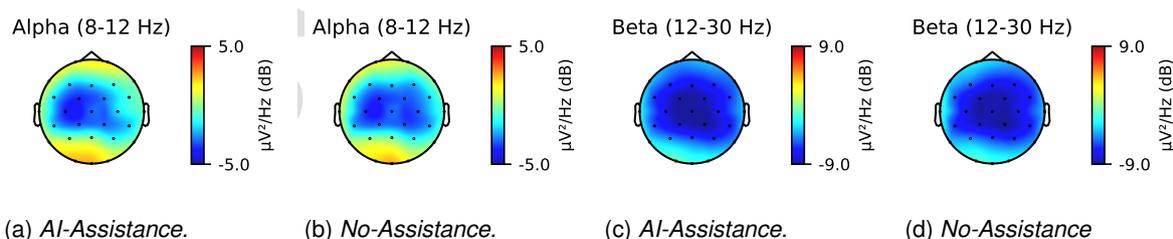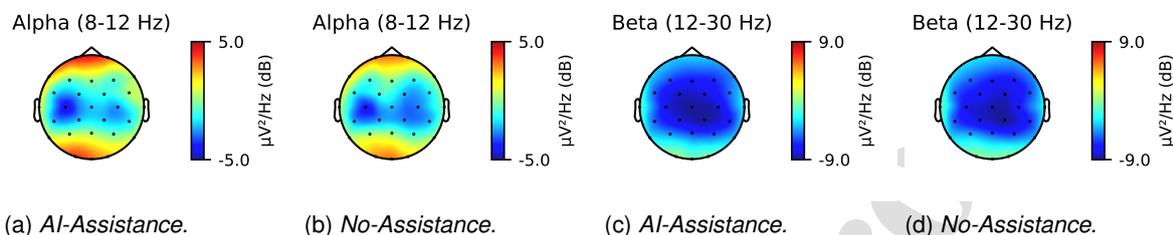
Figure 6
*Spectral Power Topographical Maps displaying Alpha and Beta frequencies under conditions with
AI-Assistance and without AI-Assistance in the scenario of Loss Cards.*

(a) *AI-Assistance.*   (b) *No-Assistance.*   (c) *AI-Assistance.*   (d) *No-Assistance.*

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 Y. Chen et al. (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 (Buchholz
et al., 2019; Bu-Omer et al., 2021; 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

646 sense of control and autonomy when interacting with intelligent systems. This consideration becomes

647 especially pertinent as we explore the integration of neurophysiological markers of a sense of agency as

648 an input for interaction, such as in BCIs. In rehabilitation, for instance, adaptive protocols could

649 significantly improve recovery outcomes by aligning therapeutic activities with the patient's specific neural

650 patterns, thereby reinforcing their sense of agency. Similarly, in educational technologies, learning

651 experiences that adapt to the student's sense of agency could make education more engaging. The

652 observed effect in alpha and beta frequencies suggests a decreased sense of agency, drawing a parallel

653 to educational areas (Klemenčič, 2015). The authors discuss the importance of fostering intentional and

654 reflective interactions between students and their environments, framed within their relational, cultural, and

655 socio-economic contexts. This perspective aligns with our findings, highlighting the need to design

656 intelligent systems that not only adapt to users' neural markers of agency but also actively reinforce their

657 sense of control and autonomy. In educational technologies, this means creating adaptive learning

658 experiences that enhance students' agentic orientation and capacity by dynamically aligning with their

659 cognitive and emotional states. By integrating neurophysiological markers as inputs, such systems could

660 potentially improve student engagement by resonating with the temporally embedded and relational nature

661 of agency, fostering deeper involvement and personalized trajectories in education (Klemenčič, 2015).

662 **4.3.3. Neurophysiological Insights into Agency with Cognitive Augmentation** Our EEG findings

663 demonstrate decreased alpha and beta spectral power with perceived AI assistance and, upon winning,

664 elucidate the neurophysiological facets of agency within cognitive augmentation. This reveals how AI

665 perceptions and outcomes affect users' neurophysiological states, influencing their sense of agency.

666 These insights inform the design of HATs that enhance abilities while preserving autonomy. We argue that

667 considering users' neurophysiological reactions to aid and feedback, we should aim to empower rather

668 than overpower user experiences. The development and design of AI should consider how it affects users'

669 sense of agency at a neurophysiological level. By considering this, Designers can create AI systems and

670 applications that align with users' sense of agency and better control over the AI outcomes, ultimately

671 leading to technologies that users accept more. Yet, it is important to consider that, as shown in this paper,

672 using neurophysiological markers to measure the sense of agency is still experimental, and thus, its

673 reliability is still to be shown; additionally, implicit methods for measuring agency might be not capture

674 entirely the user's attitudes, behaviors and feelings during interaction.

675 **4.3.4. Quantifying the Sense of Agency in Real-Time** In our analysis, we utilized an EEG-based

676 spectral analysis and based on literature (Bu-Omer et al., 2021; Dumas et al., 2012; Kang et al., 2015), we

677 demonstrated that the alpha and beta EEG metrics initially developed to measure sense of agency in a

678 motor action context also can measure the sense of agency in Human-AI interaction. Further supporting

679 this, Freeman et al. (1999) showed that EEG indices using alpha and beta bands could be employed in

680 adaptive automation systems, where the system dynamically switched between manual and automatic

681 modes based on changes in user engagement measured through these EEG metrics. Similarly, Prinzel III

682 et al. (1995) developed a bio-cybernetic system that utilized an EEG index based on beta and alpha bands

683 to modulate operator engagement in real-time, demonstrating the feasibility of using these metrics for

684 adaptive automation in cognitive tasks. This opens up new alternatives for HCI researchers to integrate

685 real-time agency measurements in their experimental designs with the advancement of EEG devices.

686 **4.3.5. Implications and Future Research Directions** Based on the knowledge gained from our

687 systematic review and analysis, we now draw future research directions to further investigate agency's role

688 in cognitive augmentation.

689   **Find the Right Balance Between Augmentation and Agency** In the context of

690 machine-assisted point-and-click tasks, it was possible to assist users up to a certain level (mild

691 assistance) without harming their sense of agency. Still, a rapid drop of agency occurred once more

692 assistance was provided (Coyle et al., 2012). A good balance between the level of AI assistance and

693 agency preservation was also identified as a crucial factor in the context of building AI-mediated social

694 connections (Wang et al., 2022).

695   This suggests that the level of intervention may fundamentally impact agency, a finding that can

696 likely be transferred to cognitive augmentation. *We recommend that designers of cognitive HATs find the*

697 *right balance between the augmentation level and the perceived agency level for their specific system.*

698 This will likely depend on the specific use case, how important a high sense of agency is for the user in the

699 given context, and how a lower level of augmentation would affect the user and their surrounding. Hence,

700 future research should investigate this trade-off between the level of augmentation and agency for different

701 types of cognitive HATs in various contexts. If a distinct threshold exists after which agency is lost, it is

702 important to identify it so that designers can make informed decisions. Finding this right balance, hence

703 leaving the user in control to some extent, may also increase the acceptance rate of the augmentation

704 technology (Shahu et al., 2022). Moreover, *we suggest considering human-computer incongruent*

705 *situations when designing cognitive HATs (Tajima et al., 2022). In particular, prevent forced failures by*

706 *design, e.g., a surgeon using an augmentation technology in medical care. Avoid forced successes when*

707 *agency preservation is highly important, but allow it in training and safety-critical scenarios.*

708   **Optimize Intervention Timing** The level of assistance and the exact timing of the intervention

709 must be considered (Kasahara et al., 2019, 2021). For motor augmentation, it was found that early

710 preemptive EMS actuation decreased the sense of agency. Identifying the optimal timing for preemption

711 resulted in faster reaction times whilst preserving the user's agency to some extent (Kasahara et al.,

712 2019), even after removing the EMS device (Kasahara et al., 2021).

713 *Likely, the intervention timing is also highly relevant in maintaining agency over cognitive*

714 *augmentation. Designers should carefully consider the exact moment the cognitive HAT assists the user.*

715 In future studies, this timing should be manipulated in controlled experiments to investigate whether a

716 sweet spot exists in which users' cognitive performance can be enhanced whilst also experiencing a high

717 sense of agency.

718 **Examine agency in different types of cognitive enhancement** People appear to be most

719 excited about brain-scanning devices that boost concentration; however, when emotional states are

720 altered, they have trust and agency concerns, as this may threaten their sense of agency (Martinez et al.,

721 2022). This indicates that the level of agency and amount of concern may depend on the cognitive ability

722 that the system augments. *We recommend that future research examines which types of cognitive abilities*

723 *can be enhanced whilst maintaining users' agency.*

724 **Reduce Cognitive Load** In head-mounted AR, W. Sun et al. (2022a) revealed a negative

725 association between mental workload and the sense of agency. Consequently, cognitive augmentation in

726 AR, which aims to reduce users' cognitive load, may lead to a win-win situation of decreased mental

727 burden whilst increasing agency at the same time. Although measuring cognitive load has been the focus

728 of HCI and user experience research since decades (Kosch et al., 2023), further research is needed to

729 establish the causal relationship between cognitive load and agency. Nonetheless, *we recommend that*

730 *designers aim to minimize cognitive workload.*

731 **Explain the System's Functionality** Explanations of AI output were found to be crucial for

732 fostering agency in AI systems (Xu et al., 2023). Similarly, users of a bodily-integrated sleep wearable

733 expressed a desire to comprehend the system's functioning to attain a high sense of agency (Semertzidis

734 et al., 2023). Therefore, *in the design of cognitive HATs, consider providing adequate explanations to*

735 *enable users to understand the system's operations and to foster a relationship of competency and*

736 *trust (Semertzidis et al., 2023) between users and the system.*

737 **Consider Ethics** Our research suggests EEG as a neurophysiological measure for assessing

738 agency during cognitive augmentation in real-time. While our results can be used to create

739 agency-adaptive interfaces that improve the experience of using cognitive augmentation technologies,

740 ethical considerations regarding autonomy, privacy, or manipulation are being discussed in the research

741 community (Cinel et al., 2019). For instance, deliberately reducing agency as a result of perceived AI

742 support could lead to long-term changes in cognitive control and decision-making, potentially manipulating

743 users' self-perception of autonomy. The potential consequences, such as altering users' beliefs about their

744 control over actions, must be carefully managed to avoid negative psychological outcomes. The handling

745 of sensitive neurophysiological data also introduces privacy and security concerns (Gordon & Seth, 2024),

746 such as the potential of correlating stimuli with measured neurophysiological activity to infer cognitive

747 states. While the field of neuroethics discusses the ethical discourse of sensing and adapting to

748 neurophysiological data (Hosseini & Kumar, 2020), the debate around agency has only started

749 recently (Goering et al., 2021). Future research should explore, implement, and evaluate guardrails for

750 ethically employing cognitive augmentation technologies that modulate agency.

751 **Resolve Performance Issues in Neurotechnology** BCI studies conducted by Hougaard et al.

752 (2022) and Hougaard et al. (2021) indicate that when individuals' sense of agency is already reduced due

753 to low performance of the BCI, computer assistance in the form of preprogrammed, fabricated input can

754 improve agency. It appears that negative consequences (here, reduced agency) of low technology

755 performance are mitigated through increased reliance on computer assistance in the form of fabricated

756 input. Moving forward, *it is crucial to resolve the underlying performance issues (the cause of the problem)*

757 *to enhance agency in BCIs, which may eliminate the need for fabricated input.*

758 **Use Objective Measures of Agency** As no gold standard on measuring agency exists yet, we

759 also looked at which agency measures were utilized in the reviewed studies. To assess agency, the

760 majority of identified studies relied on subjective self-reports by asking participants to respond to an

761 agency questionnaire (W. Sun et al., 2022a, 2022b; Venot et al., 2022), commonly a single-item 7-point

762 Likert scale question (Kasahara et al., 2019, 2021; Y. Sun et al., 2023; Tajima et al., 2022). In some of the

763 included VR studies, the agency measure was included in a self-report questionnaire concerning

764 embodiment (Gauthier et al., 2021; Miura et al., 2021; Takada et al., 2022; Zhang et al., 2022), ownership

765 illusion (Jun et al., 2018), or general VR experience (Seinfeld et al., 2022).

766 Several of the studies included did not directly measure the sense of agency. Instead, agency was

767 identified as a theme based on qualitative study results (Martinez et al., 2022; Mueller et al., 2023; Sali

768 et al., 2012; Shahu et al., 2022; Thieme et al., 2023; Wang et al., 2022; Xu et al., 2023; Zolyomi & Snyder,

769 2020). However, four studies did not specifically measure the sense of agency (Mercado-García et al.,

770 2021). Instead, some assessed user's perceived control (Ahmad et al., 2022; Hougaard et al., 2022;

771 Hougaard et al., 2021). Only two studies utilized objective measures of agency. Coyle et al. (2012)

772 assessed intentional binding as an implicit measure of the sense of agency, using the Libet clock method

773 in one experiment and interval estimation in the other. Finally, only one study used physiological measures

774 of agency based on EEG data, applying spectral power analysis and brain activity analysis (W. Sun et al.,

775 2022b).

776 The advantage of objective agency measures is that they do not rely on introspection and

777 subjective reports, whereas self-reported agency can be biased and confounded (Wolpe & Rowe, 2014).

778 In future studies, we recommend enhancing objectivity by combining subjective measures such as

779 questionnaires with objective, physiological measures of agency (Wolpe & Rowe, 2014), for example,

780 using EEG data (Jeunet et al., 2018; W. Sun et al., 2022b), as our results have shown that state-of-the-art

781 EEG correlates for sense of agency apply for the context of cognitive augmentation. *Therefore, we*

782 *recommend that researchers include neurophysiological measures when assessing the sense of agency*

783 *during cognitive augmentation.*

784 **4.3.6.   Limitations** While this review aims to examine the agency's role in cognitive augmentation, most

785 publications in our review are related to motor augmentation and other domains related to augmentation,

786 such as neurotechnology, AR/VR, and AI. Based on insights from these related studies, we formulated

787 research directions for cognitive HATs. However, further lab-controlled experiments are required to validate

788 whether our review findings can be transferred to cognitive augmentation. Another limitation is that,

789 although we developed a clear inclusion criteria set, a single reviewer conducted the screening, which may

790 introduce subjective bias despite our steps to consult a second author for ambiguous cases. Furthermore,

791 we limited our database search to ACM Digital Library and IEEE Xplore for their strong HCI coverage, but

792 this scope may have excluded relevant interdisciplinary work found elsewhere.

793   The analyzed dataset employed EEG as a physiological measure of agency, offering valuable

794 insights. However, the limitations of EEG technology, particularly its cost and obtrusiveness, restrict its

795 applicability in real-world HCI settings. Future research should investigate alternative physiological

796 correlates of agency that are more ecologically valid and suitable for integration into consumer devices.

797 Promising alternatives include exploring measures such as heart rate variability, electrodermal activity, and

798 pupil dilation, which offer the potential for unobtrusive and cost-effective assessment of agency in diverse

799 HCI contexts.

800   We acknowledge that EEG-based band measures (e.g., alpha band) can be influenced by several

801 confounding factors such as attentional shifts, cognitive load, and fatigue (Klimesch, 2012). To mitigate

802 these issues, we employed within-subject comparisons and counterbalancing in our experimental design

803 and used ICA-based preprocessing to reduce artifacts related to fatigue and movement. Nonetheless, we

804 emphasize that in future work, EEG should be interpreted in conjunction with behavioral and subjective

805 data to robustly infer agency. Future work should consider triangulating EEG with additional metrics such

806 as pupillometry, galvanic skin response, or self-report scales (e.g., intentional binding tasks or real-time

807 Likert ratings) to provide a more comprehensive view of user agency.

808   While this analysis employed objective EEG measures to measure agency, it did not employ an

809 explicit self-reported measure like the Sense of Agency Scale (Tapal et al., 2017). This deliberate choice

810 aimed to avoid sensitizing participants to the specific assessed metric, as the original authors were

811 concurrently manipulating causal attribution through verbal descriptions. However, this approach may have

812 limited the ability to directly compare our findings with existing literature that relies on self-reported

813 measures. This study utilized objective EEG measures to assess agency, deliberately avoiding explicit

814 self-reported measures, such as the Sense of Agency Scale (Tapal et al., 2017). This decision was made

815 to prevent participants from becoming sensitized to the specific evaluated metric, particularly as causal

816 attribution was being concurrently manipulated through verbal descriptions. However, this approach may

817 have limited the ability to directly compare our findings with prior research that relies on self-reported

818 measures. Future studies could explore the integration of objective and subjective measures to gain a

819 more comprehensive understanding of agency in similar contexts. Such an approach would shed light on

820 the relationship between explicit self-reports and implicit measures of cognitive agency. This is especially

821 compelling given related research on motor augmentations, which has demonstrated correlations between

822 implicit metrics and self-reported measures (Yun et al., 2019).

5. Conclusion

824   Human agency in the context of cognitive augmentation technologies remains an under-explored

825 area despite its critical importance in HCI. This work addresses this gap by reviewing two decades of HCI

826 research on agency and related domains. The analysis reveals a lack of studies directly investigating the

827 sense of agency within cognitive augmentation. Drawing upon insights from the reviewed literature, we

828 propose future research directions to advance the understanding of agency in this context. Furthermore,

829 we present an analysis of an experimental study exploring whether EEG-based agency metrics originally

830 developed for a motor action context can capture the sense of agency in cognitive augmentation. Our

831 findings demonstrate the feasibility of this approach and reveal a decrease in perceived agency when

832 participants are explicitly informed about AI assistance. In the future, specific factors that support or hinder

833 agency, for instance, considering (i) a balance between assistance and agency preservation, (ii)

834 intervention timing, and (iii) different types of cognitive enhancements, should be explored further.

835   **6. Conflicts of Interest**

836   The authors do not declare any conflict of interest with the submitted work.

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Whose Mind is it Anyway? A Systematic Review and Exploration on Agency in Cognitive Augmentation

Steeven Villa*[a], Lisa L. Barth[a], Francesco Chiossi[a], Robin Welsch[c], Thomas Kosch[b]

[a] LMU Munich, Frauenlobstrasse 7a, 80337 Munich, Germany.

[b] HU Berlin, Rudower Chaussee 25, 12489 Berlin, Germany.

[c] Aalto University, Konemiehentie 2, 02150 Espoo, Finland.

* Corresponding author:
Steeven Villa
steeven.villa@ifi.lmu.de,
LMU Munich, Frauenlobstrasse 7a, 80337 Munich, Germany
Phone: +33766349410

Conflict of interest

Ethic approval information

Declaration of 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 declare the following financial interests/personal relationships which may be considered as potential competing interests: