Towards Augmenting Humans in the Field: A Review of Cognitive Enhancement Methods and Applications

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Abstract

Efforts have always been deployed to surpass limitations in human cognitive abilities to enhance aspects such as task accuracy, work effectiveness and error management. Cognitive enhancement is a field aiming at improving human cognition in order to overcome those limitations. It bears important interest from the human factors community given its potential for reducing errors in complex operational environments. Yet, cognitive enhancement strategies are rarely used outside the lab and practical applications are scarce. The current paper presents a brief summary of the literature on human cognitive enhancement and discusses key operational applications of the main methods reported in this field. Using a human factors perspective, the paper also outlines how such techniques could be integrated into decision-support tools to support operators facing cognitive challenges in complex operational domains, including those experiencing functional limitations preventing them to contribute to the workforce.

Keywords: cognitive enhancement; neuroscience; applied cognitive psychology; human factors; decision-support systems

Introduction

Humans have always been captivated by the idea of surpassing their inherent limitations. In that regard, efforts have been deployed by the scientific community to augment humans using techniques such as performance-enhancing drugs, prosthetics, medical implants, human-machine teaming and several other strategies (Moore, 2008). Such interest not only concerns physical limitations, but also those pertaining to cognitive abilities, especially because of their importance for avoiding human errors. According to Cinel et al. (2019), human cognitive enhancement represents "the improvement of the processes of acquiring/generating knowledge and understanding the world around us" (p. 2). The goal of cognitive enhancement is to *augment* human capacities to facilitate task performance, instead of reducing the resources necessary to carry out the task. In short, this means that human cognitive enhancement aims at increasing brain function rather than making the task easier.

Particularly driven by neuroergonomics (Parasuraman, 2003) and brain-computer interface research (BCI; Birbaumer et al., 2006), cognitive enhancement can optimize information processing capabilities of the brain. The interventions developed accordingly are expected to facilitate task performance and help face difficulties incurring from cognitive challenges related, e.g., to workload, distraction, multitasking, sustained attention or complex decision making and problem solving. These cognitive challenges are often experienced in multiple work domains and during everyday life (e.g., Jett & George, 2003; Loukopoulos et al., 2009).

In that regard, cognitive enhancement not only received attention from the scientific community, but also from military organizations who see potential applications for national defense and security (e.g., UK Ministry of Defence, 2021). Despite its relevance for practical applications mainly related to neuroergonomics and BCI, cognitive enhancement methods are rarely used outside the lab, and practical applications as well as representations in published roadmaps are scarce (Cinel et al., 2019; see also Brunner et al., 2015; Future Brain/Neural Computer Interaction [BNCI] Consortium, 2012; Wiseman, 2016). Although this can be in part explained by the relatively young development status of some neuroscience technologies, the lack of field applications of human cognitive augmentation methods might also be driven by the limited knowledge of these methods in the human factors, cognitive systems engineering and cognitive ergonomics communities.

Hence, the goal of the current paper is to provide a brief state-of-the-art of the existing cognitive enhancement techniques and to outline possible applications for operational contexts. To reach this goal, we first describe the main techniques found in the literature to augment cognition that could be used as interventions in the field. Then, we discuss the possible applications of such methods for operational contexts and describe the implications of using those techniques to improve human performance.

Review of Cognitive Enhancement

Research has identified many abilities that human operators must hone to optimally perform their daily tasks. Although all cognitive abilities can be beneficial to the work of human operators (e.g., the capacity to multitask for military-related jobs; Chérif et al., 2018), the most important ones may vary across work domains (e.g., prospective memory, automatic processing and control of attention switching for pilots, see Loukopoulos et al., 2009; memory, vigilance and decision making for infantry soldiers, see Nibbeling et al., 2014).

Different methods can be used to determine the key cognitive processes involved in a given task and, ultimately,

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the best cognitive abilities to augment. Cognitive task analyses represent a good technique to characterize a full task procedure or a workflow to disentangle all the subtasks and their underlying processes (see, e.g., Shachak & Reis, 2009). Another way is by defining specifically what brain areas are activated while a given task is performed. Such a neuroergonomic approach has been widely used to understand the underpinnings of different cognitive tasks. For instance, Rocha et al. (2020) were interested in developing an intervention to enhance performance during a shooting task and they discovered through electroencephalographic measures significant implication of the right dorsolateral prefrontal cortex (DLPFC). Hence, they developed an intervention to specifically augment the neurological activity in the right DLPFC. Once a specific cognitive function or process ascribed as critical for a given task or work is defined, different methods can be used to augment its capacity. Cognitive enhancement literature raises many strategies, which can be split into three main families: neurostimulation methods, biochemical methods, and behavioral methods.

Neurostimulation Methods

Neurostimulation is a technique relying on electrical current to alter neuronal activity (polarization and de-polarization), either its resting potential or firing rate. This method specifically aims a neuron, a group of neurons or a brain area. To aim at a specific brain area, the person conducting the intervention must apply the current on the appropriate zone, which can be found either from literature (theoretical approach) or using neuroimaging techniques (empirical approach). Depending on how the current is applied, the electrical activity in the brain on the chosen area can be augmented or diminished. Neurostimulation techniques comprise the following (see Table 1): Transcranial electrical stimulation (tES), transcranial magnetic stimulation (TMS), focused ultrasound (FUS), and deep brain stimulation (DBS). These techniques vary on their functional mechanisms, but also on their invasiveness (whether it requires direct brain access or if it can be placed above the scalp), portability (whether they represent portable or bulky equipment), spatial resolution (the precision regarding the specific area that is targeted), and temporal resolution (the delay between the actual intervention and the outcomes measured; see Cinel et al., 2019).

An important bulk of the literature on neurostimulation concerns stimulation of the DLPFC, a cortical region typically related to mechanisms of working memory, attention, and to preparation and inhibition of motor responses (e.g., Szurhaj et al., 2003). Evidence of cognitive augmentation with DLPFC stimulation is large, especially for working memory improvement (e.g., Au et al., 2016; Fregni et al., 2005; Hammer et al., 2011; Ke et al., 2019; Murphy et al., 2020). In a systematic review, Feltman et al. (2020) reported 11 articles focusing on this goal, including seven that found significant evidence of working memory improvement. A meta-analysis published by Russowsky Brunoni and Vanderhasselt (2014) also supported that stimulation of the DLFPC by TMS could significantly improve both accuracy and reaction time on the *n*-back tasks. Other functions such as attention (Chan et al., 2021; Gladwin et al., 2012; Nelson et al., 2016) and higher cognitive functions, such as creativity and inhibitory control (Cerruti & Schlaug, 2009; Fecteau et al., 2017; Friehs & Frings, 2018), can also benefit from stimulation of the DLPFC.

Table 1: Description of neurostimulation techniques.

Technique	Description
tES	Mild current injection over the scalp that modulates cortical excitability in either a hyperpolarizing (via anodal stimulation) or depolarizing (via cathodal stimulation) direction. Can be of direct (tDCS), alternating (tACS), pulsed (tPCS) or of random (tRNS) frequency.
TMS	Magnetic field application with coils to alter neural firing of neurons in underlying cortical tissue over the scalp.
FUS	Novel technique relying on low-intensity focused ultrasound pulsations, allows to reach deep-brain areas non-invasively.
DBS	Invasive technique relying on implanted neurostimulators and single electrodes inserted directly into the brain or directly over the cortex. Can only be done following a craniotomy.

Benefits of neurostimulation over other neocortex areas can also be found. Clark et al. (2012) developed a tDCS intervention over the right inferior frontal and right parietal cortex to enhance visual search and object recognition abilities. They showed that participants receiving 2-mA current over these regions were significantly better at finding concealed objects within a background scene compared with a sham (i.e. 0.1 mA) condition. In fact, stimulating modality-specific areas of the brain—rather than higher-order zones—shows promising outcomes. Such has been supported by studies involving stimulation over the Wernicke's area (Flöel et al., 2008), visual areas (Herpich et al., 2019; Hilgetag et al., 2001), and motor areas (Galea & Celnik, 2009) to support language, visual and motor tasks, respectively.

Yet, the positive effects of neurostimulation are sometimes debated (e.g., Andrews et al., 2011; Mottaghy et al., 2000; Mull & Seyal, 2001). Horvath et al. (2015) conducted a meta-analysis on the effects of anodal and cathodal tDCS among normal populations for online (i.e. during tDCS delivery) and offline (i.e. after tDCS had been administered) applications on several aspects including working memory, executive control, and language. Of the 59 analyses they ran, no significant support was found. It must however be noted that the authors analyzed the effects of tDCS in several separate analyses, largely reducing their statistical power. Moreover, the brain areas included varied largely. Hill et al. (2016) conducted a meta-analysis on the impact of anodal tDCS over the DLPFC for online and offline stimulation of working memory. They also compared healthy populations with clinical populations. Results found significant evidence of memory enhancement among healthy subjects, but specifically for offline applications on reaction time. On the opposite, clinical populations benefited from anodal tDCS only for online applications and on their accuracy on the working memory tasks. According to the authors, the online effects of anodal tDCS depend on membrane potential changes while offline effects may be driven by changes in synaptic strength through the modulation of Gamma-aminobutyric acid (GABA) and glutamatergic activity. In clinical populations, membrane potential changes might alter the cortical environment enough to lead to subsequent changes in behaviour. For healthy populations with typically optimal homeostatic cortical activity, online changes may not be sufficient to incur observable changes, but long-term alteration may produce improvements in reaction time.

Overall, cognitive enhancements of low to moderate effect sizes can be observed following neurostimulation, but these effects can be influenced by many factors such as the technique used (e.g., tDCS vs. TMS), the cortical area stimulated, the intensity of the simulation and the type of stimulation (i.e. anodal vs. cathodal). Moreover, individual differences in the susceptibility to cognitive enhancement via neurostimulation exist and some people may respond in a lesser way than others (e.g., clinical vs. healthy populations, see Hill et al., 2016; high dopaminergic activity in Met allele homozygous individuals, see Wiegand et al., 2016).

Biochemical Methods

A vast part of the literature on cognitive enhancement is devoted to biochemical interventions (e.g., Harvey & Keefe, 2015). Such strategy is mainly used among clinical populations to mitigate cognitive symptoms related to mental health issues such as dementia, mood and psychotic mental issues, improving attention, executive functions, memory, and social cognition. The potential of these interventions among healthy subjects has also been evaluated for cognitive enhancement. Drugs used for this purpose are called nootropics (Ricci, 2020). Typically, nootropics either inhibit or increase secretion of specific neurotransmitters.

Many studies first concern drugs affecting the secretion of acetylcholine (ACh). ACh mediates a high range of cognitive functions including perception (Erskine et al., 2004), attention (Robbins et al., 1989), memory and learning (Kopelman, 1986), emotion (Kamboj & Curran, 2006), and sleep (Kim & Jeong, 1999). ACh levels increase with nicotine, cholinesterase inhibitors, varenicline and glucose, and drop with scopolamine and mecamyalamine. ACh exerts sensory neuromodulation for the top-down processing of relevant stimuli (Ghatan et al., 1998; Jacobsen et al., 2004). Both physostigmine (Bentley et al., 2008) and nicotine (Rose et al., 2010) can reduce parietal activity during selective attention paradigms. Finally, ACh activity in medial temporal structures is positively correlated to benefits on memory encoding (e.g., Antonova et al., 2011; Kukolja et al., 2009).

Research has also been conducted on dopamine (DA) and norepinephrine (NE) nootropics. DA and NE, sometimes called catecholamines, are crucial for several cognitive activities including vigilance, action, reward association, learning and memory, and their action is considered highly intertwined, even redundant (Ranjbar-Slamloo & Fazlali, 2020). Methylphenidate, modafinil, and caffeine can impact catecholamine levels (Caviola & Faber, 2015). Methylphenidate increases DA and NE secretion and shows effects on memory performance (Ilieva et al., 2015; Repantis et al., 2010; Roberts et al., 2020) and inhibitory control (Roberts et al., 2020). Yet, effects on attention are globally absent (Repantis et al., 2010), sometimes even negative (Rogers et al., 1999; but see Linssen et al., 2014; Roberts et al., 2020). Modafinil is a prescription drug for narcolepsy (Ballon & Feifel, 2006; Volkow et al., 2009). It can improve attention in healthy subjects, regardless of their sleep deprivation level (Battleday & Brem, 2015; Franke et al., 2014; Repantis et al., 2010). Positive effects on sustained and selective attention (Baranski et al., 2004; Dean et al., 2011; Schmaal et al., 2013), and on memory updating (Roberts et al., 2020) were also raised. Finally, caffeine intake improves sustained attention and alertness in simple tasks (Einöther & Giesbrecht, 2013) and sometimes in complex tasks (Heatherley et al., 2005; Rogers & Denoncourt, 1998). It has also been related to memory improvements and shorter response speed to new stimuli (Borota et al., 2014; Riedel et al., 1995; Warbuton et al., 2001). Still, some catecholamine nootropics depend on the user's baseline capacity and effects seem higher for low-performing individuals (Finke et al., 2010). It can impair performance among high-performing persons (Farah et al., 2009; Mattay et al., 2000) and disrupt attention control (Rogers et al., 1999) and creative thinking, flexible thinking and judgement (Baranski et al., 2004; Mohamed, 2014; Müller et al., 2013). The impact of caffeine also depends upon habitual intake, age and personality (Attwood et al., 2007; Nehlig, 2010; Smith, 2002).

A third set of studies concern glutamate (Glu). Glu is one of the most important neurotransmitters for the central nervous system and electric synaptic activity. It is a key substrate for learning and memory (Dauvermann et al., 2017). One of the well-known nootropics associated with Glu is ampakines. It represents a class of drugs increasing Glu by coupling with AMPA receptors to enhance long-term potentiation (Arai & Kessler, 2007). Ampakine is considered a good candidate for cognitive enhancement by the scientific community (Urban & Gao, 2014). For instance, Ingvar et al. (1997) showed that improvements in visual recognition, motor performance and general intellectual functioning could be improved by ampakines intake, as opposed to a placebo, which was ascribed by the authors to selective effects on memory (see also Lynch et al., 1997; Wezenberg et al., 2007).

Generally, cognitive enhancement can be achieved using the types of nootropics presented here (see Table 2 for a summary). Interestingly, efforts are deployed by military organizations to evaluate the potential of these drugs to support soldiers in different contexts (Saletan, 2008; Taylor

& Keys, 2003). Though this strategy seems interesting, it also possesses important limitations. Urban and Gao (2014) provided a review of the negative side effects of nootropics, raising adverse effects (e.g., tachycardia, insomnia, dizziness and anxiety) and issues ensuing from the time of consumption and dosage. As put by Greely et al. (2008), an appropriate risks-benefits balance must be reached, long-term effects among healthy individuals need to be better understood, and risks, benefits and alternatives must be properly understood before relying on this strategy (see also Cakic, 2009).

Table 2: Summary of effects of biochemical cognitive enhancement according to neurotransmitter type.

Neurotransmitter	Nootropic	Impact
ACh	- Nicotine - Cholinesterase inhibitor - Scopolamine - Mecamyalamine - Varenicline - Glucose	Sensory processing, memory, attention
DA and NE	- Methylphenidate - Modafinil - Caffeine	Memory, inhibitory control, attention
Glu	- Ampakine	Memory, intelligence

Behavioral Methods

The third method for cognitive enhancement concerns behavioral interventions. According to Caviola and Faber (2015), these are considered as effective as biochemical cognitive enhancement methods (see also Sachdeva et al., 2015, for a review). Methods of behavioral cognitive enhancement include, without being limited to: domain-general cognitive training, exposure to restorative material, and mind-body practices. Table 3 summarizes these methods.

Table 3: Behavioral methods of cognitive enhancement.

Method	Description	Impact
Cognitive training	Training on general ability to augment specific abilities	Near transfer (improvement on task similar to training) and far transfer (improvement on task involving different cognitive functions)
Attention restoration	Viewing and engaging with nature stimuli	Restores depleted executive attention, in turn improving performance on cognitive tasks
Mind-body practices	Sleep; physical exercise; yoga and meditation	Facilitate memory consolidation; increases cerebral efficiency; improvements in attentional capacities

Cognitive Training Domain-general cognitive training can be construed as any form of training focused on a general ability rather than an action or a specific aspect of a task (e.g., Ballesteros et al., 2018). The idea behind cognitive training is to go beyond the mere acquisition of skills, and reach general improvement of abilities (Schmiedek et al., 2010). The ultimate goal is to train a person on a given (cognitive) task to help them become better on tasks involving the same set, but also different sets of cognitive abilities (near and far transfer, respectively). For example, Maraver et al. (2018) asked participants to either train on an inhibitory control task or a working memory task. They showed that participants training on an inhibitory control task could improve their performance on a reasoning task (i.e. Raven matrices). However, those training on working memory did not improve on the Raven task, and both groups also failed to show far transfer on a cognitive flexibility task (i.e. the AX-CPT). This study showed possibility for reasoning to benefit from inhibitory control training. Au et al. (2015) conducted a meta-analysis of the studies aiming at improving fluid intelligence with training on working memory capacity. They showed evidence of small but significant positive effects of *n*-back training in improving measures of fluid intelligence. Other meta-analyses also reached the same conclusion regarding the potential of working memory and executive function training to conduce to near and (small) far transfer in several age groups (Karbach & Verhaeghen, 2014; Scionti et al., 2020; Teixeira-Santos et al., 2019). Training sessions on computer programs or even videogames have also been shown to induce generic cognitive benefits (e.g., Dresler et al., 2013; Kozhevnikov et al., 2018; Olfers & Band, 2018).

Yet, some authors argue against the possibility for far transfer. Sala et al. (2019) ran a meta-analysis on working memory training including second-order investigations to control for a majority of confounding variables. They showed that near transfer can be observed, especially for toddlers and young children and to a lower level among adults and elders. Regarding far transfer, however, effect sizes and true variance levels equaled zero when controlling for placebo effects and publication bias (see also Sala & Gobet, 2019), suggesting that far-transfer effects may be circumstantial. Still, one must remain prudent when criticizing near and far transfer effects given the difficulty of comprehensively assessing all the potential (unmeasured) transfers (e.g., on executive attention, complex problem solving, or even emotional control and social abilities). Moreover, individual differences play a modulatory role on the possibility for transfer in training (e.g. Bednarek et al., 2021; Jaeggi et al., 2013), and these effects might be difficult to isolate over a meta-analysis.

Exposure to Restorative Material According to attention restoration theory (ART; see Kaplan, 1995), attention is a resource that can become depleted with overuse. From Kaplan and Berman’s (2010) perspective, the directed and voluntary form of attention is a resource that is common for all executive functioning and self-regulation activities.

According to ART, stimuli that do not draw on this resource thus have the potential to allow restoration of attention. Nature would be particularly efficient at augmenting attention capacities given its high preference over other environments, promoting automatic and effortless attention.

A large body of evidence about attention restoration properties of nature can be found. A key study published by Atchley et al. (2012) exposed the benefits of being immersed in nature for creative complex problem solving following a four-day trip into nature. Other studies also found positive impacts of nature exposure on other attention-related cognitive tasks such as proof reading (Hartig et al., 1991), control of Necker Cube patterns (Tennessen & Cimprich, 1995), and backward digit span task (Berman et al., 2008, Exp. 1). Such findings could also be observed with exposure to virtual nature or with mere images of nature (e.g., Berman et al., 2008; Berto, 2005). Stevenson et al. (2018) reviewed 49 individual outcome measures from 8 generic cognitive domains. They outlined that working memory, cognitive flexibility and attentional control could be specifically improved after exposure to natural environments with low to moderate effect sizes, moderated by the type of exposure (real vs. virtual). Due to the benefits triggered by nature, interaction with and exposure to such restorative environments/stimuli can represent an interesting avenue to restore depleted attentional resources and consequently enhance cognition. In this regard, elements of nature and interactions with nature have been integrated in and around schools and workplaces to help enhancing depleted mental resources of students and workers (see Marois, 2020, for a review). Optimal engagement toward the nature stimuli would however help in increasing the cognitive benefits (e.g., Duvall, 2011; Pasanen et al., 2018; Szolosi et al., 2014).

Mind-Body Practices In their daily lives, humans typically turn toward sleep, physical exercise, and meditation to restore their fatigue. Sleep can be used as a cognitive enhancement intervention. As a pre-task intervention, short sleep periods (or naps) vary in efficiency and effect size depending on their duration and on the memory system that needs boosting. Mander et al. (2011) observed improvements in episodic-memory learning for subjects who took a 100-min nap before a learning phase compared with a no-nap condition. Studies also showed that performance on subsequent retrieval can be improved by post-task sleep (e.g., Diekelmann & Born, 2010; Lewis & Durrant, 2011; Stickgold & Walker, 2013). Two hypotheses are proposed for these effects (see Diekelmann, 2014, for a review): one contending that memories are reactivated during sleep (active system consolidation theory) and the other stating that brain connections become depotentiated during sleep, except for the connections related to recent memory representations (homeostasis hypothesis).

Physical exercise also shows potential to enhance cognition (e.g., Dietz, 2013; Moreau & Conway, 2013; Vazou et al., 2019). Improvements in cognitive functioning following physical activity would be driven by several causes including better cerebral circulation, alteration of neurotransmitters synthesis/degradation, and optimized cerebral plasticity (see Antunes et al., 2006, for a review). Literature however indicates that it is not the mere physical exercise that impacts cognitive performance (e.g., Etnier et al., 1997), but rather how it is performed. For example, Eckardt et al. (2020) showed that instability resistance trainings led to benefits on working memory, processing speed and response inhibition compared with two other more “stable” training conditions. According to the authors, the benefits of the exercise were augmented by the “cognitive challenge” associated with remaining stable during the exercise. The nature of the activity performed thus plays an important role. Other moderators of the benefits of physical activity on cognition include aspects such as the intensity of activity, the type of cognitive ability assessed, and the duration of physical activity (see Brisswalter et al., 2002; Moreau & Chou, 2019; Tomporowski & Pesce, 2019).

Yoga, mindfulness training and meditation are related to sleep and napping given their ability to restore one’s energy. Yet, they also produce unique effects because of the nature of the cognitive activity they promote. Two main types of meditation are typically considered, each raising different effects on cognition and brain activity (see, e.g., Fox et al., 2016; Fujino et al., 2018). Focused attention meditation implies narrowing one’s selective focus on a specific external object or internal experience. In this situation, top-down control of attention is used, promoting persistence metacontrol policies and serial thinking, as well of suppression of irrelevant material (Immink et al., 2017), leading to enhanced sustained attention as well as response inhibition (e.g., Zanesco et al., 2018; Zeidan et al., 2010). Open monitoring meditation rather encourages attention to widen to let the person be more receptive to any stimulus or sensorial, metacognitive and affective experiences. It promotes awareness, flexible policies and parallel thinking, reducing competition between relevant and irrelevant information, giving rise to positive effects for sequence learning performance (Immink et al., 2017). Nevertheless, a recent meta-analysis on meditation effects conducted by Sedlmeier et al. (2012) found only a 0.28 effect size. While the authors present some methodological issues that might explain this weak effect size, one must still remain prudent in anticipating observable cognitive benefits of meditation. Similarly, despite evidence of cognitive improvements among yoga practitioners (Brunner et al., 2017; Rocha et al., 2012; Subramanya & Telles, 2009), effect sizes of yoga benefits would be moderate for attention, processing speed, and executive functioning (cf. Gothe & McAuley, 2015).

Applications and Implications of Operational Cognitive Enhancement

Three families of cognitive enhancement methods were discussed: neurostimulation, biochemical and behavioral. The neurostimulation method aims at directly intervening on brain synaptic activity depending on the cerebral region upon which stimulation is provided. Biochemical methods rely on nootropics, which represent either agonists or antagonists of specific neurotransmitters to impact different cognitive processes. Finally, behavioral interventions such as cognitive training, exposure to restorative stimuli, and mind-body practices can also contribute to augment cognitive capacities.

While these interventions may improve cognition, some may be more or less suited for workers in operational contexts. Biochemical interventions may be difficult to implement for medical reasons. Neurostimulation techniques can also meet some resistance. Though literature contains comprehensive guidelines on how to securely apply neurostimulation (Lefaucheur et al., 2017; Thair et al., 2017), ethical aspects must be considered (Hildt, 2019; Lapenta et al., 2014; Voarino et al., 2016). Therefore, a comprehensive risk assessment and precise study protocol must be carefully elaborated for neurostimulation methods. Behavioral interventions might be easier to implement given their reduced risk and complexity. Regardless of the technique, aspects such as the targeted cognitive function, personal factors, the time scale, side effects, availability and social acceptance must be considered before implementing an intervention in a workflow (Dresler et al., 2019).

Once the technique (or combination of techniques) identified, it is necessary to define how it can be implemented into the operators' workflow. Two ways can be considered: as a pre-task intervention or as a countermeasure-type intervention, during a task. In the first situation, one would benefit from the intervention as a "shield" against further cognitive challenges or a way to mitigate chances of observing phenomena such as cognitive overload, auditory distraction or vigilance loss. For example, security surveillance operator's performance has been shown to be positively correlated with cognitive flexibility (Marois et al., 2021); hence, given the benefits of nature exposure for this type of cognitive process (Stevenson et al., 2018), an operator could start their work shift by exposing themselves to virtual landscapes. Countermeasure-type interventions would rather be used as a tool to recover one's state to try to reach back their baseline/optimal state. A soldier facing vigilance loss during a mission could e.g. benefit from modafinil intake due to its effect on sustained attention (Dean et al., 2011). Note that some interventions may be more appropriate for pre-task support (e.g., cognitive training), countermeasures (e.g., biochemical), or sometimes both (e.g., neurostimulation).

While these interventions could be used in a circumscribed manner, depending on the subjective feeling of the user or on predefined work practices, a more optimal way would be to integrate them into a closed-loop decision-support system relying on bidirectional BCI methods. Such system can be developed to trigger a cognitive enhancement strategy either up until a state of enhancement is reached (e.g., as a pre-task intervention), or until a nominal baseline state is re-attained (i.e. as a countermeasure intervention). In one direction, the functional state of the user and information on their cognitive resources/state would be provided to a system via BCI methods and, in the other direction, an intervention would be conducted until the loop is closed and the state has returned to a certain level. For example, Karthikeyan and Mehta (2020) developed a system triggering a tDCS intervention with pre-set stimulation parameters to augment vigilance in near-real time by relying on a biobehavioral model (for other examples of closed-loop systems, see Basu et al., 2021; Li et al., 2020; Zelmann et al., 2020). An interesting avenue would be to automatically adjust the intervention, not only to find the proper moment, but also to intelligently tailor it according to the user's individual factors and context. In that regard, optimization algorithms could be used, as is already the case for certain medical interventions (e.g., Ballesta & Clairambault, 2014; Beumer et al., 2021).

Overall, the integration of cognitive enhancement strategies into operational domains could have important benefits. Because it can be used to help a person reaching their optimal baseline following a period of depletion or rather to augment their normative level—incurring sometimes potential for long-term benefits—this integration could benefit several high-stakes, error-prone domains characterized by important cognitive challenges. Human cognitive limitations can indeed lead to errors in many high-risk domains including but not limited to command and control domains (Grier, 2015; Hodgetts et al., 2015, 2017), piloting (Loukopoulos et al., 2009), and multiple military professions (Chérif et al., 2018). An integration of such techniques into a closed-loop system would allow users to receive timely and adapted support which might contribute to augment efficiency and reduce mistakes. Such application could also support the integration of people facing cognitive limitations and intellectual disabilities into the paid workforce. Indeed, adults with intellectual disabilities face extremely high rates of unemployment and poverty across the world (Emerson, 2007). Given the importance of job training and performance for employee well-being and job retention (Ellenkamp et al., 2016), such application of cognitive enhancement could support some difficulties faced by this population and, in turn, contribute to increasing their inclusion into the workplace, as well as workforce diversity.

Conclusion

Cognitive enhancement represents an innovative and burgeoning field aimed at improving cognitive abilities in periods of suboptimal resources. Here, we reviewed the main techniques reported in the literature related to neurostimulation, biochemical intervention and behavior-based methods. While each of those strategies may vary in acceptability and applicability, all of them have potential for operators to reach an enhanced state or to recover specific cognitive abilities. Future work toward their integration into operational contexts should aim at examining their impact over observable key performance indicators across different domains. Then, efforts should be carried out to discover different biobehavioral proxies that could be integrated into bidirectional BCIs to develop tailored, closed-loop cognitive enhancement systems that could be used for the online support of operators. In pursuing this objective, workers might ultimately perform better, hence improving efficiency, security, but also diversity and inclusion.

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