Cognitive flexibility training for impact in real-world settings

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Abstract (100-120 words)

Interacting with complex and dynamic environments challenges the brain's ability to adapt to change. This key ability known as cognitive flexibility involves learning the structure of the environment, switching attention between features, dimensions and tasks, and adopting new rules in the face of uncertainty. Training cognitive flexibility has strong potential to improve adaptive behavior across the lifespan with impact in real-world settings (e.g. educational, clinical). Here, we review evidence on the role of cognitive training in improving executive functions and the factors that may enhance the effectiveness of training programs. We propose that personalized and adaptive training programs that focus on the multifaceted abilities comprising cognitive flexibility are key for promoting adaptive behavior and lifelong learning in real-world settings.

Highlights

1. Cognitive flexibility is a multifaceted ability that is critical for adaptive behavior and resilience.
2. Training cognitive flexibility has potential to transfer to real-world skills.
3. Individual, societal, cultural differences may impact the effectiveness of cognitive flexibility training programs.
4. Enhancing engagement and motivation through games may improve training of cognitive flexibility in real-world settings.

Introduction

Cognitive flexibility (CF), a multifaceted ability that is critical for successfully adapting to the needs and changes in dynamic environments[1] encompasses a range of skills, including attentional shifting, strategy updating, response to feedback, reversal learning, exploration and task switching (Figure 1). In particular, task-switching involves switching between different tasks or actions that are defined by specific stimulus-response associations, as demonstrated in the Trail Making Test or Task Set-Switching paradigm[2]. Set-shifting involves learning new rules with feedback and transitioning between cognitive sets that are defined by perceptual cues (e.g. color, shape), as tested by the Wisconsin Card Sorting task (WCST) and the Intra-/Extra-Dimensional Set Shifting task. Reversal learning requires adjusting to changes in established reward-contingency associations. These skills collectively underpin our capacity to flexibly adapt to change and modify our behavior in dynamic environments[3].

This review highlights recent work on the role of training cognitive flexibility in promoting adaptive behavior and key considerations (Table 1) for cognitive flexibility training with potential impact in real-world settings (e.g. educational, clinical).

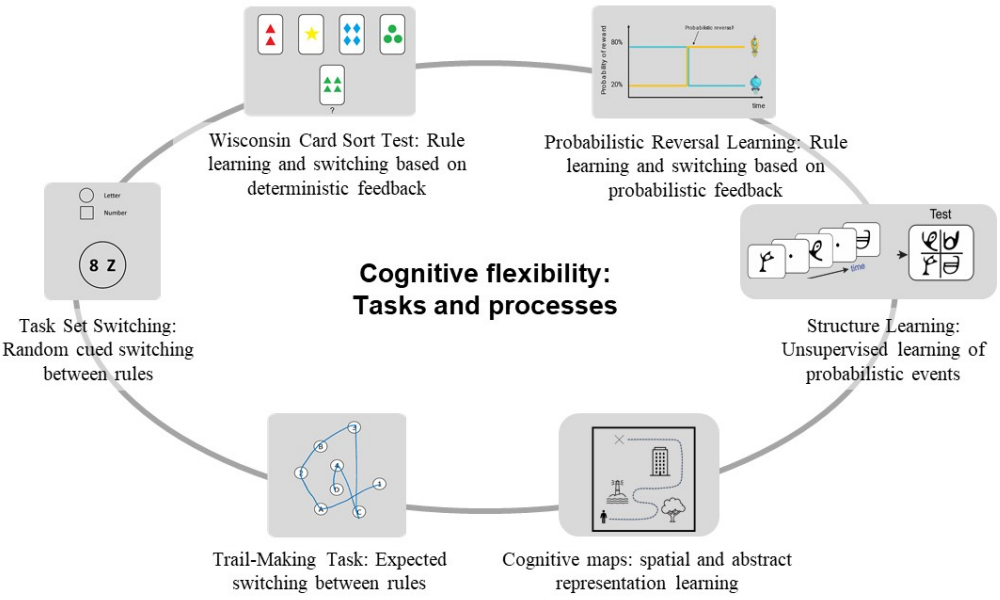


Figure 1. Tasks and cognitive processes relevant to training of cognitive flexibility

Cognitive flexibility: brain mechanisms

Studies investigating the neural substrates of cognitive flexibility highlight the role of fronto-striatal circuits[4–6]. Animal studies have shown that the lateral prefrontal cortex (LPFC) is engaged in extradimensional shifts, while the orbitofrontal cortex (OFC) is key for reversal learning processes[7]. Human neuroimaging studies have shown similar results; in particular, the ventromedial PFC (vmPFC) has been implicated in extradimensional shifts (i.e. when a different stimulus dimension becomes task-relevant), the lateral OFC in reversal learning (i.e. when a non-target stimulus becomes target) following positive feedback, and the medial OFC in reversal learning following punishment[8]. Further, set-shifting has been shown to engage the dorsolateral prefrontal cortex (DLPFC), consistent with the cognitive demands of reconfiguring sets, while task-switching has been shown to engage the anterior cingulate cortex (ACC) and the pre-supplementary motor area (pre-SMA), that are known to be involved in executive control and managing multiple task demands. Taken together, these findings provide evidence for the nuanced and varied neural pathways underpinning the multiple aspects of cognitive flexibility, highlighting its complexity and the diverse neural architecture that supports flexible behavior.

Recent developmental studies propose that childhood and adolescence are critical periods for the maturation of brain regions that support cognitive flexibility[9], with evidence suggesting that this process may start as early as 9 months[10]. This suggests that training of cognitive flexibility during early development may be critical for flexible behavior in adulthood. In particular, DLPFC and pre-supplementary motor area (pre-SMA)/SMA have been implicated in tasks requiring switching or attentional shifting in children[1].

Cognitive flexibility and learning under uncertainty

Recent work highlights the potential link between cognitive flexibility and probabilistic learning under uncertainty. The ability to shift between different strategies and mental representations—key aspects of cognitive flexibility—is critical when solving problems under uncertainty; e.g. when navigating a new city or learning a new language. Recent studies employing a dynamic structure learning task (i.e. learning the underlying temporal structure of the environment without explicit feedback) demonstrate that individuals adapt to probabilistic changes in the statistics that govern the environment and exploit them to make predictions in novel settings[11–13]. In particular, individuals change their decision strategy from matching (i.e. extracting exact sequence statistics) towards maximization (i.e. extracting the most probable outcome in a given context) to reduce uncertainty and improve their ability to learn predictive statistics in variable environments[12]. Interestingly, individual decision strategies are shown to engage dissociable brain mechanisms[12–15]; that is, matching engages the visual cortico-striatal pathway, whereas maximizing engages fronto-striatal networks. Taken together, these studies suggest that structure learning under uncertainty facilitates flexible learning by switching between decision strategies that are supported by distinct brain circuits[16]. Future studies are needed to investigate whether training interventions using dynamic structure learning paradigms may facilitate cognitive flexibility.

Cognitive training and real-world transfer

Most cognitive training programs have focused on skills related to memory, perceptual and attentional control[17]. As cognitive training aims to improve skills that are important for learning (e.g. problem-solving and flexible thinking) and real-life outcomes (e.g. educational attainment), its effectiveness is assessed based on three different types of generalization (i.e. transfer effects). Near-transfer involves improvement in tasks that assess the same processes as the training task but with different materials (e.g. stimuli) and/or task structure. Far-transfer involves improvement in tasks that require skills related to the cognitive domain trained by the

intervention (e.g. training on a task involving spatial abilities that leads to improvements in verbal reasoning[18]). Finally, ecological transfer involves improvement in activities of daily life (e.g. critical thinking) and academic performance.

Executive functions have been associated with academic ability and educational attainment[19]. In particular, meta-analysis studies have reported associations of working memory and cognitive flexibility with reading comprehension, reading efficiency and mathematical skills[20,21]. These findings have motivated the design of cognitive training programs for translation to educational settings[22,23]. Despite associations between executive functions and real-world outcomes (e.g. academic attainment), cognitive training has mostly shown near-transfer on related domains[24,25] while evidence for far- or ecological-transfer effects[26] remains limited. Studies investigating the effect of cognitive training on academic abilities (e.g. math, reading, recalling of stories) have reported some beneficial effects of these interventions in typically and atypically (e.g. ADHD or dyscalculia) developing learners. Although most of the training programs have focused on working memory[19,27,28], studies focusing on inhibitory control and cognitive flexibility training also show beneficial effect on academic abilities (i.e. language and mathematical performance in school exams, sentence comprehension in a standardized reading task[29–31]). Taken together, previous findings call for caution in interpreting cognitive training impact and highlight factors that may contribute to far- and ecological-transfer effects following training of executive functions (Table 1).

First, recent work suggests that cognitive training is enhanced if the content of the training task relates to the intervention target (e.g. generalization to academic skills)[32,33]. For example, training children's cognitive flexibility skills by incorporating mathematical operations as task rules should benefit math performance and contribute to a better learning experience in mathematics, including mathematical flexibility[34].

Second, cross-cultural studies have highlighted the importance of socio-cultural differences and task-context (e.g. stimulus relevance) for participants from different countries[35]. For example, an individual's personal, historical, and cultural experiences may modulate cognitive load and influence task performance and training outcomes[32,36].

Third, increasing engagement with cognitive training programs enhances motivation to learn and continue to train, enhancing their effectiveness. In particular, the perceived significance of the knowledge acquired, instructional support, interactive engagement (e.g. using computerized games), and teacher-student relationship for school-based cognitive training programs may determine the effectiveness of cognitive flexibility interventions in improving educational outcomes[32]. For example, cognitive training has been shown to improve performance in healthy young adults (18-30 years) in the domain of sustained attention and concentration when using a game on an iPad, to increase motivation during training[37]. In healthy older adults (60 - 80+ years), cognitive functions across a range of domains could be trained using games on mobile phones[38]. A meta-analysis of 16 studies with 1543 participants has confirmed that the domains of processing speed, verbal memory and working memory can be successfully trained in older adults[39]. Finally, reward based on task performance may enhance motivation with the potential caveat that offering excessive external rewards for an already internally rewarding behaviour may reduce intrinsic motivation[40].

Further, recent work provides evidence that personalized and adaptive cognitive training using computerized games that enhance engagement and motivation to learn impacts cognitive performance in patient populations with neurological or psychiatric disorders. For example, cognitive training with a learning and memory game on an iPad was shown to improve performance not only in the training tasks but also in clinical measures for stroke patients, patients with Mild Cognitive Impairment (MCI) and schizophrenia[41–43]. This work provides promising insights for potential applications of cognitive flexibility training programs in

clinical settings. For example, patients with Obsessive Compulsive Disorder (OCD)[6] or premanifest Huntington's disease (pre-HD)[5] show impairments in cognitive flexibility tasks. In OCD, impairments are linked to disrupted connectivity brain circuits known to be involved in cognitive flexibility; that is, between the caudate nucleus and ventrolateral prefrontal cortex, as well as the putamen and dorsolateral prefrontal cortex[6]. Similarly, in pre-HD, cognitive impairments correlate with altered dorsolateral prefrontal cortex-caudate connectivity[5]. These findings propose that training in cognitive flexibility tasks may enhance decision-making abilities and adaptive behavior in these patients.

Finally, methodological issues may obscure transfer effects in cognitive training studies. Some measures may be more sensitive than others; for example cognitive training may result in improved academic potential, rather than academic performance; the latter is commonly used in cognitive training studies but may lack sensitivity to detect transfer effects[44]. Further, individual differences at baseline performance may obscure transfer effects if measured at group level[45]. Therefore, more precise measures of individual performance may provide higher sensitivity in measuring far-transfer effects following cognitive training.

Training cognitive flexibility

Research on cognitive flexibility training is still in its infancy; yet, emerging research proposes that training cognitive flexibility may be effective in improving cognitive skills. Conditions that engage skills at the core of cognitive flexibility may facilitate improvement; that is, introducing variability in training protocols, uncertainty, switching between task-relevant dimensions and across tasks. Further, skills related to creativity that engage novel and divergent thinking (e.g. generation, remote association) may support cognitive flexibility.

The evidence for far-transfer effects following cognitive flexibility training is currently scarce but promising. Initial studies suggest notable improvements in task-switching with transfer

effects on different areas of executive functioning[46,47]. Friedman & Miyake[48] have demonstrated through confirmatory factor analysis the potential impact of cognitive flexibility in real-world settings. Further studies suggest beneficial effects of cognitive flexibility training on academic abilities, (i.e. language, performance in math tests, sentence comprehension in standardized reading tasks in children[49–51]. Training programs that target the diverse cognitive processes involved in cognitive flexibility may have stronger potential to show benefits that generalize to real-world settings.

Individual variability in cognitive training

Cognitive training outcomes are influenced by diverse factors, including age, socioeconomic status (SES), personality traits, and genetics. These factors influence the effectiveness of training programs which varies greatly across individuals[45,52]. For example, Karbach and Kray[47] found that generalization of task-set switching training was enhanced in adults and impaired in children when training involved novel task demands in each training session. Genetic predisposition is also found to modulate the effectiveness of cognitive training in cognitive flexibility. For example, Val/Val homozygous carriers of the COMT Val[158] Met polymorphism exhibited higher transfer in task-switching than Met/-carriers, following video game training[53]. Further investigation on individual differences in cognitive flexibility training is crucial for designing personalized cognitive training programs[25] and clarifying mixed results in generalization (i.e. near- vs. far-transfer) of cognitive training[17].

Interrogating the processes underlying cognitive flexibility may enhance our understanding of individual differences in training outcomes. Computational modelling allows us to dissect the processes involved in cognitive flexibility by decomposing behavioral responses into process-specific modelling parameters[54]. For example, modelling of structure learning tasks enables tracking individual decision strategies and how they change to help individuals learn, optimize

task performance, and generalize[11]. This is important for understanding how training individuals to change decision strategies may help optimize performance to solve complex tasks under uncertainty.

Conclusions

In sum, training that targets the multifaceted abilities that comprise cognitive flexibility and support adaptive behavior are critical for the effectiveness of cognitive training programs in real-world settings (e.g. educational, clinical). Further, personalized adaptive designs that incorporate developmental, societal, and cultural factors and support enhanced engagement with training through games may increase the success of cognitive flexibility training and promote far-/ecological-transfer benefits to academic abilities[19,22,30].

Table 1. Designing training programs to improve cognitive flexibility

1. Task-level considerations
1.1. Training higher-order control processes (i.e. abstract reasoning), rather than task-specific strategies (e.g. shifting)
1.2. Engaging neural and cognitive substrates that overlap with skills required for transfer
1.3. Personalized and adaptive training targeted to the participant performance (e.g., enabling "level" progression)
1.4. Training that challenges curiosity and inference abilities (e.g. changing probability of getting higher scores, changing the task modalities or implementing game-like elements)
2. Participant-level considerations
2.1. Sample-size
2.2. Individual differences (e.g. SES, educational level, culture, personality, motivation, socio-emotional traits)
2.3. Developmental stage (e.g. children, adolescents, young adults, older adults)
2.4. Neurodevelopmental conditions (e.g. dyslexia, dyscalculia, ADHD)
3. Context-level considerations
3.1. Delivery modality (i.e. computerized, online, in-person)
3.2. Delivery setting (i.e. individualised, classroom, home-based, community)
3.3. Cultural norms (i.e. training uses elements familiar to the individual's culture)
3.4. Engagement (i.e. computerized games to improve motivation)
4. Theoretical and measurement level considerations
4.1. Define the level of performance measurement (e.g. accuracy, speed or computational-modelling index)
4.2. Define the set of skills being trained and how they relate to cognitive flexibility
4.3. Define the far-/ecological-transfer effects indicators and whether they are domain-specific (e.g. math, reading comprehension) or domain-general (e.g. intelligence)

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