Making Brain Training Effective

A Review of Training Features that lead to Durable Performance Increases Beyond the Training Context

Floris Martijn Verhoeven

Supervised by Stella F. Donker

In almost all fields of experimental psychology, enhancements in performance have been achieved after extensive training. These improvements however, are classically confined to the context in which the learning takes place. Considering the relevance of real-world training tasks or rehabilitation paradigms, this context specificity is a problem for the aim of general learning. Nevertheless, recent studies employing video games and working memory tasks as training have produced learning effects that have generalized to previously untrained tasks. This review discusses the mechanisms and essential features that cause this transferability with the aim to provide guidance for future training paradigms. By identifying the characteristics responsible for the success of these regimens, like including tasks that span multiple modalities, minimizing the use of specific strategies and attaining maximal participant engagement, recommendations can be made about implementing these features to achieve a maximal learning effect, increasing the effectiveness of the training paradigm.

INTRODUCTION

Some 20 years ago, Anders Ericson and Andreas Lehmann conducted a study in which they managed to improve the amount of digits one participant, S.F., could remember. It had long been established that the average persons' digit span capacity was approximately 7 (Miller, 1956), but after extensive training this participant was able to remember a series of 79 digits (Ericsson & Lehman, 1996). This miraculous feat was achieved by *chunking*, combining discrete pieces of information and associating them. With chunking, S.F. was able to circumvent the hours of practice associated with learning and training by using a cognitive strategy and almost instantly and explicitly improve his digit span capacity. However, when his ability to recall letters was assessed, he got a less-than-impressive score: six. Thus, the improved performance in a digit span task did not transfer to an alternative context, a letter recall task. A skill that can be used outside of the trained context is referred to as a *transferable skill.* When thinking about *transferability* it is perhaps easiest to consider the example of physical activity: when a professional soccer player is targeting his upper leg strength during a gym routine, his aim is to gain an on-the-pitch advantage through an increase in sprinting speed or leaping height, rather than being able to leg press a certain amount. Similarly, someone who frequently engages in bike riding is indirectly improving his running performance (Suter, Marti, & Gutzwiller, 1994). In this example, there is no direct transfer of a specific skill, but riding a bike improves general fitness, which proves to be beneficial for running performance. Along these lines, companies ranging from video game company Nintendo (Nintendo Co., Kyoto, Japan) to research companies like Lumosity (Lumos Labs, San Francisco, CA, United States), have developed a variety of software packages in an attempt to increase a general cognitive capacity, analogous to the example of general fitness. These mental workouts are designed to test and increase attention, memory and problem solving abilities. Whereas the well-known software of Nintendo largely focuses on the entertainment element of *brain training*, several companies go beyond this and promise clinical success: Neuronix (Neuronix Ltd., Yokneam, Israel), for instance, was founded in 2008 with the mission *"[…] to find a method for modifying the course of treatment of Alzheimer Disease (AD), and thus provide long-term improvement in the quality of life for patients […]".*

This mission statement by Neuronix frames the two critical elements that determine the effectiveness of a training paradigm: transferability and durability. In order for the overall quality of life for patients and customers to be enhanced, the skills learned using the software need to transfer to real-life situations. As has been demonstrated with the example from S.F., training on remembering digits did not prove to be advantageous for overall memory or more specifically, letter recall. In an ideal scenario of generalization, we can for instance improve our intellectual and attentional capabilities as well as augmenting our athletic performance just by training on one single task. Then, the effects of training need to be long lasting, as in most cases the application of the learned skill takes place well after the acquisition of the skill. In the example of the soccer player, the transfer test is during the final match, not in the gym. Durability also distinguishes short-term learning effects from *true learning* as temporary (e.g. mood) effects affect learning outcomes (Schmidt & Bjork, 1992). If the observed changes persist through time, this is considered successful learning. In other words, the goal of training in real-world settings should be to create a long-term improvement in performance after the training with the ability of transferring that skill to both related and unrelated tasks.

With the commercialized brain training industry hitting the billion-dollar mark somewhere in 2012 and the expectation it will expand to 6 billion USD in 2020 (SharpBrains, 2012), it is the right time to assess the effectiveness of these and other paradigms, like video gaming and working memory training, before they are considered a universal cure. Therefore it is the aim of this review to support all types of future training and rehabilitation studies by identifying training regimens that lead to improvements in performance that generalize beyond the training context and assess which features training interventions need to incorporate in order to positively enhance performance. I will first discuss a broad range of cases from scientific literature that demonstrate that improvements in performance can be achieved by sustained training. However, just like the example from Ericsson and Lehman (1996), most of these studies show enhancements that have been confined to the training environment or specific training parameters. Centered around an influential theory of skill transfer – the hierarchical learning theory - I will continue by evaluating the accumulated evidence regarding the various elements and conditions in the training paradigm that have shown to positively influence the success of a training paradigm. Based on the knowledge currently available, I will conclude by giving several suggestions with regards to future research.

SPECIFICITY IN TRAINING

Examples of some sort of learning are found in almost any field in experimental psychology, ranging from S.F. and his immense digit span (Ericsson & Lehmann, 1996) to expert cigar rollers (Crossman, 1959). Because of the substantial amount of evidence accumulated over the years regarding learning which show that training someone is indeed possible, the most important question to answer is not if brain training works, but how to make it work so that the effects are long lasting and transfer to other tasks. In order to better understand this, several cases will be discussed that demonstrate that improvements in performance can be obtained through training, opposing the original belief that skills are hard-wired (Sagi & Tanne, 1994). However, the attained advances are highly specific to task context, which goes against at least one of the critical elements involved with true learning: *transferability*.

In the field of visual perception, advances through training frequently have been achieved. In one experiment that had participants train on discriminating whether a line was above or below a reference line (*a Vernier acquity task*) performance gradually increased during the first day of training. Even on the first trials of the second day, the performance was at the same level as at the end of the first day. However, when the orientation of the stimulus was rotated by 10 degrees, the performance was back to its original level from day one (Fahle, 2004). Here, the improvements from extensive training on the first day were diminished by a slight change in task context, showing no transferability. Analogously, identifying the direction of dot motion is open to practice, but showed a large specificity for speed (Saffell & Matthews, 2003). A similar specificity has been observed in a motor learning study in which participants who were trained on a visually guided manual reach improved their spatial accuracy. However, when no visual feedback was present during the retention test, their performance was worse than during the acquisition of the training phase (Mackrous & Proteau, 2007). Another motor learning case comes from a prism adaptation study: during prism adaptation, a recalibration of the motor system is required to counter for lateral displacement induced by the prism goggles. A series of experiments showed that the adapted motor maps are highly specific to either the trained movement or the trained position (Redding & Wallace, 2006). In both motor-learning examples the learned skill does not transfer outside of the context in which the skill was learned. The same specificity is problematic in the domain of cognitive training. Several studies looking to counter the cognitive decline in aging populations have created intervention studies based on specific techniques to increase memory performance. Method of loci is one of these mnemonic techniques, in which participants are asked to store the piece of information and visualize placing it in a physical space, like on a nightstand or in the garage. Using the method of loci technique is similar to the chunking technique in the digit span experiment, as it is successful at improving performance on a particular memory task (Cavallini, Pagnin, & Vecchi, 2003; St Clair - Thompson, Stevens, Hunt, & Bolder, 2010). However, like with chunking, the results do not show any generalization to disparate task contexts, making it unsuitable for a training paradigm with *true learning* as aim.

Due to the recent upsurge of commercial brain training software, special attention is dedicated towards the exploration of the effectiveness of this software. Despite the fact that there are several differences between the existing packages available, most programs are built around simple tests used in psychological assessments, like matrix reasoning, symbol search or arithmetic problems. Similar to the examples in the previous paragraph, it has been demonstrated that by extensively training on these tasks, participants (or in this case: customers) can attain durable improvements in their performance, lasting up to 5 years

(Willis et al., 2006). But again, the enhancements in performance are narrowly restricted to the parameters of the training and evidence for transfer to related tasks is sparse: in one study where elderly were trained using the POSIT software (Posit Science, San Francisco, CA, United States) and retested on a large standardized battery of neuropsychological assessments only showed an increased auditory memory at this post-training tests (Mahncke et al., 2006). In another, participants reported fewer difficulties in everyday life after being trained on a visual search task. Although this appears to be the desirable far transfer, these outcomes are self-reported and not based on tests of cognitive abilities, making it prone to placebo-like influences, as the conviction that training must have an effect on performance might instigate this increase in performance (Morrison & Chein, 2011).

One similarity in all of the aforementioned paradigms is the relative separation of task domains: all tasks have been designed for a specific purpose (e.g. increasing digit span capacity; Ericsson & Lehmann, 1996) and it is only this element that is being trained. I will use the remainder of the review to argue that, even though the obtained results in these training paradigms are notable, this high specificity is problematic, especially when the aim is to see learning effects that persist over time (*durability)* and show a benefit in unrelated tasks and contexts (*transferability)*. In an attempt to explore what aspects of a training paradigm result in durable and transferable effects, I will now briefly discuss an influential theory that addresses the issue of specificity and argues that by targeting domain-general mechanisms, rather than increasing performance by training on a specific task or using a strategy, true learning can be realized.

HIERARCHICAL LEARNING

One prominent theory to explain the workings of transfer stems from perceptual learning (PL) and is called the Reverse Hierarchy Theory (Ahissar & Hochstein, 2004). The theory proposes that learning is a top-down guided process, with the most salient information available at lower levels. Starting off with the highest level, learning progresses backwards to lower levels if the information accessible at the higher levels isn't sufficient to solve the task at hand. Although this theory was developed to explain observations from the perceptual field, it is an appealing model to the whole domain of learning because of the way it accounts for the separation between specificity and generalization: tasks that are handled by higher level structures will show transfer, whereas the low level organizations will have more specificity. It is perhaps best understood by considering a *psycho-anatomy logic* example from PL: if subjects are trained on a set of bar-shaped stimuli, that all have the same orientation, followed by a change in orientation in a second task, this second task will activate a different population of simple (low-level) neurons that do not overlap with the population from the first task, resulting in a lack of transfer and no savings on the second task. However, according to the theory, if participants were trained on higher-level features, this would have generalized to novel orientations (Ahissar & Hochstein, 2004). They tested this hypothesis by manipulating the task difficulty in a orientation detection task in which participants were asked to spot an object with a dissimilar orientation in an array of homogeneously oriented bars. They found that when the task was made easier, by making the odd bar 'pop out', the learned skill transferred better to untrained orientations. On the other hand, the most difficult tasks showed high orientation specificity. They argued that the easier tasks could be solved at high cortical levels in the visual pathways, because of the large signal to noise ratio. The more difficult tasks required more salient information, which is only present at lower levels.

A similar theory, the neuronal overlap theory, hypothesized that if the training and transfer task invoke activity in the same brain regions, transfer will occur. It has been argued that, because of the overlapping activity of the left inferior frontal gyrus (IFG) in the region of the pars triangularis (Brodmann's Area 45) in working memory and episodic memory tasks, there should be a transfer of skill between these two tasks (Lustig, Shah, Seidler, & Reuter-Lorenz, 2009). To test the neuronal overlap principle, Dahlin et al. (2008) trained participants on a memory updating task, and investigated the training efficiency with two transfer tasks: an n-back task and a Stroop task. Although both these transfer tasks rely on executive functioning, it had previously been shown that memory updating evoked striatal activity, a feature shared by an n-back task. The experimenters therefore argued that skill would transfer from the training task to the n-back task, but not to the Stroop task, which was later confirmed by their results (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008). Similarly, optical topography revealed activation of the lateral prefrontal cortex during tests of both fluid intelligence and visuospatial working memory. After two months of training on a visuospatial working memory task, measures of fluid intelligence (the ability to solve novel problems independent of prior experience; Cattell, 1963) were significantly increased (Kuwajima & Sawaguchi, 2010).

Thus, in order to design a task that generalizes well to a transfer task, the training and transfer task need to be handled at a shared high-level region within the hierarchical organization. Tasks that are looking for a high generalization to other tasks can and should be designed specifically to achieve this high-level processing by implementing the following elements: a highly adaptive paradigm that adapts to the capacity of the participant as to maximize engagement, minimize the use of specific strategies or automization and include tasks that span multiple contexts or modalities. These requirements can roughly be summarized in three critical features: complexity, variability and motivation. Since these elements are highly related, it is most informative to illustrate their importance by discussing cases from two very successful strains of training research: video game training and working memory training. Although these fields seem highly idiosyncratic, they share the key features mentioned above, resulting in a larger amount of skill transferred and long-lasting improvements.

VIDEO GAMES

It has consistently been demonstrated that active players (at least 5 hours a week) of action video games (AVGs) show enhanced performance on a variety of retention tests. More specifically, they distribute their visual attention more efficiently (Green & Bavelier, 2003), can track objects at greater speeds (Boot, Kramer, Simons, Fabiani, & Gratton, 2008), and have lower task-switching costs (Boot et al., 2008) compared to non-players. The observed differences between expert- and non-expert gamers in various cognitive domains are interesting, but is at risk for a population bias: it is not hard to imagine that people who have superior task-switching abilities will thrive in contexts where these abilities are rewarded, like video games (Green & Bavelier, 2008). Therefore it is more relevant to consider the several studies that investigated the causal relationship between video games and enhanced functioning by subjecting non-video gamers to a game-playing intervention. Most studies note improvements in subjects' performance in a visual search task (Feng, Spence, & Pratt, 2007; Green & Bavelier, 2003), increased multiple object tracking capacity (Green & Bavelier, 2006), lower attentional blink (Green & Bavelier, 2003), and higher spatial resolution and visual acuity (Green & Bavelier, 2007). Similarly, intervention studies with elderly have successfully increased the capacity to detect visual changes, increased their reasoning power and lowered their memory costs (Basak, Boot, Voss, & Kramer, 2008).

Observing these results we can conclude that there is support that playing action video games is a form of learning that can result in transfer to standard laboratory-administered test of visual ability and executive functioning. One of the strong arguments for the use of video games in training is its inherent complexity. Even though these games are not intended for the purpose of having a beneficial effect on cognitive performance, most action video games have a strong memory component, require multitasking, fast object recognition and high attentional and motor abilities in order to be successful, all high-level features of executive functioning. Whereas in typical paradigms the training is broken up into several subdomains, video games combine them, demanding a high level processing across various domains. Previous work has demonstrated that there is a strong advantage for subjects who practiced under random conditions. Even though there were worse during the training itself, they outperformed the group who practiced in a blocked-design (Ahissar & Hochstein, 2004; Schmidt & Bjork, 1992). These results are especially significant since hardly any real-world task appears in a precisely separated blocked context. The fact that AVGs are relatively complex makes them the preferred category of video games when it comes to the training of skills. With other video games, like the well-known puzzle game Tetris, there is a significant difference between the skills of players compared to non-players, but a 12-hour training intervention did not improve the non-players beyond a control group (Sims & Mayer, 2002). Although Tetris has a strong visuomotor component, it lacks unpredictability and has only a limited amount of objects to recognize (Achtman, Green, & Bavelier, 2008). The unpredictable nature of video games allows does not allow for automated decision being made, and predictions made by the player will often be inaccurate, forcing the behavior to update and improve. Studies have shown that actively avoiding doing things on ‘autopilot’, by breaking down activities in sub-goals has a positive influence on daily life activities (Levine et al., 2007). For a comprehensive review of the types of video games and the effects of playing them, please refer to Cohen et al. (2007).

Another highly important feature of AVGs is the adaptive nature of the video game. Generally speaking, the difficulty of the levels increases incrementally as players progresses through the game (Green & Bavelier, 2008), therefore constantly challenging them at the limits of their abilities. This serves an important motivational purpose: when the task difficulty scales with subject performance, an ideal level will be reached that is both stimulating and attainable, making it maximally engaging. This aligns with the ‘zone of proximal development’ theory in which motivation and learning are highest when the training is marginally more demanding than the current capacities of the individual (Vygotsky, 1978). In fact, in one study that failed to show significant transfer, self-reported motivation was extremely low, with 49 out of 78 participant strongly stating they would never use the training software (Nintendo Wii Big Brain Academy) outside the study’s context, indicating a low level of engagement (Ackerman, Kanfer, & Calderwood, 2010). Similarly, Owen et al., (2010) who saw no transfer effects, also report the lack of engagement as a potential shortcoming in their design (Owen et al., 2010). Underlining the importance of engagement, a post-test analysis of motivation in a successful training study showed that components of intrinsic motivation explain two-thirds of the individual differences in transfer (Jaeggi, Buschkuehl, Jonides, & Shah, 2011).

Moreover, even though players have to meet certain objectives in these games, these goals are difficult to reach with the use of one specific strategy. Due to the large variability of the tasks and stimuli, the focus is largely on exploratory learning, rather than following a single predetermined (domain-specific) strategy (Rebok, Carlson, & Langbaum, 2007). Indeed, various training studies using a single strategy, like the method of loci or the digit span study, do not show generalization of results to other tasks or domains. However, broader approaches that combine multiple strategies lead to higher levels of far transfer (Lustig et al., 2009; Rebok et al., 2007). Moreover, self-generated improvements in performance are more long lasting than strategies based on instructions, and participants are more likely to continue using their own strategy after the training period has ended. A possible explanation for the importance of implicit or exploratory learning opposed to using a standard strategy for a task comes from Schmidt and Bjork (1992) who argue that randomness in practice forces participants to come up with a creative solution on every trial, maximally engaging the subject and encouraging thorough processing. Besides that, it could be that using an explicit strategy cuts short the required time for durable neuronal changes that are necessary for transfer to occur (Klingberg, 2010).

An additional advantage of the high diversity of video games is that with more tasks at hand, the chance of one or more of these tasks having some sort of beneficial effect on performance is increased. However, this does cause a methodological concern about the amount of control experimenters have on these video games. The complexity of an AVG like Call of Duty (Activision, Santa Monica, CA, United States) does not allow for any interference by a researcher, making it overly difficult to identify what element of the gameplay is causing what improvement. Furthermore, even though these training-induced improvements in untrained tasks are a step in the right direction, they are largely restricted to visual attention and do not appear to transfer beyond that (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008).

WORKING MEMORY TRAINING

The second example of successful transfer of skill comes from working memory (WM) training. These paradigms do not have the same limitations as action video games, as they are fully malleable by the investigators running the training. Even though the tasks employed in WM training are seemingly less multifaceted than AVGs, various studies report transfer to tasks that are fundamentally unrelated to the task being trained on (*far transfer).*

One of these successful paradigms (Jaeggi et al., 2008) uses a unique double (both visually and auditory) n-back task (Kirchner, 1958) to train the WM capacity of their participants. In this task, a subject was asked to store the information from *n* trials ago, and match this with the information presented at the current trial. With improving performance, the *n* increased, thus forcing the participant to keep updating the working memory storage with more information. After the training, measures of fluid intelligence were taken using a variety of tests, showing that the WM training on the n-back task had improved their performance on the fluid intelligence tasks (Jaeggi et al., 2008, 2011). These promising results have increased the focus on working memory training, and the success of the training has been expanded by recent findings from a range of training studies that not only investigated the transfer of WM skills to other tasks, but also investigated changes in neural activity as a result of training. To be more specific, a specially designed computer program using both verbal and visuospatial working memory tasks was used to train stroke patients (Westerberg et al., 2007), healthy volunteers (Olesen, Westerberg, & Klingberg, 2004; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009) and children with ADHD (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002) leading to improved WM performance on untrained tasks, transfer to other cognitive tasks (a Stroop task, a test of response inhibition) and in some cases to inductive reasoning tasks (Raven's Progressive Matrices task)(Klingberg et al., 2005, 2002). A study in which participants were scanned before and after training sessions found increased activity in frontal- and parietal lobes (Olesen et al., 2004), areas strongly associated with WM capacity (Edin et al., 2009), suggesting training induced plasticity. Interestingly, whereas usually an increased task proficiency leads to lower activation (due to automation of performance), it has been suggested that because of the unique features of WM (e.g. keeping information active regardless of familiarity with the stimuli) an increase in activity is witnessed here (Olesen et al., 2004).

Contrary to AVGs in which the complexity ensured there was not one task the same (possibly resulting in no low-level neuronal overlap); WM capacity is a fundamentally a high-level skill that is commonly used in a large variety of tasks. This sets working memory aside from visual and motor skills employed in AVGs, which are highly domain specific. The way this is thought to work is well explained by the hierarchical model explained earlier; if the training- and transfer task share the same (high-level) component, doing a range of these tasks will reinforce learning at the shared level. In fact, it is believed that function of WM is a strong predictor for, and thus in some way associated with, cognitive performance and academic success (Conway, Kane, & Engle, 2003; Morrison & Chein, 2011; Rohde & Thompson, 2007). It is exactly because of this relationship between working memory and real-world skills that this particular trait lends itself for experimenting with implicit improvements and transferability, making it more appealing than for example a medical approach using psychostimulants (Holmes et al., 2010).

One thing that WM training does have in common with AVGs is the adaptive design of the paradigm. In the n-back task, the performance was analyzed after each block, and the level (*n*) was adjusted accordingly. The commercial software used by Klingberg and colleagues (CogMed, Pearson PLC, London, UK) also lets participants perform at a level slightly above their current capacity (Edin et al., 2009; Klingberg, 2010; Klingberg et al., 2005, 2002; Olesen et al., 2004; Thorell et al., 2009; Westerberg et al., 2007). Successful WM training studies seem to understand the combined importance of motivation and task difficulty: it seems as if generalized learning is a U-shaped function of complexity and motivation. If a task is too easy, there is a risk of low compliance to the task because of boredom. A task being too difficult can lead to a loss in motivation as well. One study found that, upon further analysis of their results, the participants that improved the least during the training sessions were the ones that were frustrated with the level of the task (Bjork & Bjork, 2011).

DISCUSSION

After examining the current state of the literature, considering an important theoretical model explaining results and identifying several extrinsic factors crucial to obtain generalized learning I would like to guide future research on the potential application of brain training by proposing several points that require careful consideration.

The assumed importance of an adaptive paradigm that is tailored to the individual raises an important question about for whom training is most useful. Although certain factors are not controllable variables like complexity and motivation to some extend are, the age of the participant group seems to influence the generalization potential of the trained skill. An appealing study making a direct comparison between the skill transfer in younger- and older adults showed transfer to a handful of fluid intelligent tests in younger adults, but no transfer at all has been observed in the elderly (Schmiedek, Lövdén, & Lindenberger, 2010). Similar results are obtained in a explicit learning task (using mnemonics) in which children benefited more from exercise than older adults (Brehmer, Li, Müller, von Oertzen, & Lindenberger, 2007) and an associative memory task in which there was a negative correlation between age and performance gain (Shing, Werkle-Bergner, Li, & Lindenberger, 2008). One possible explanation for the limited success in older adults comes from a study comparing pre- and post-training neural activation after a WM training paradigm. Among a variety of interesting conclusions, they found that older adults had lower striatal activity compared to younger adults, both before and after the training intervention, while also showing no skill transfer (Dahlin et al., 2008). Due to the important role the striatum has in executive functioning, it could be that the age-related decline in activity is limiting the successful transfer. An alternative explanation for the lower increase in performance might be the initial level of the subject: who start off with a lower ability will improve more, simply because there is more room for improvement. This is something that is seen for example in studies with groups with WM deficits(Holmes et al., 2010; Klingberg et al., 2002). Subjects who score high on measures of cognitive plasticity benefit more from memory training, and it is well-known that cognitive plasticity declines with age (Brehmer et al., 2008; Calero & Navarro, 2007). With this in mind, it is of the utmost importance to carefully investigate the subject group characteristics before initiating a training study. I suggest that the emphasis in further research should be on investigating both for whom training interventions might be most advantageous and what programs are most probable to show general learning effects.

In an attempt to design a training task with the highest generalization potential I want to encourage the use of novel techniques that explore the possible use of neuroimaging data to select and improve a training task based on the involvement of specific brain regions in the transfer task. Considering the practical validity of training in developing an intervention paradigm, it is an appealing idea that transfer might be predicted by the neural overlap in task related activity (Dahlin et al., 2008; Jonides, 2004; Kuwajima & Sawaguchi, 2010; Olesen et al., 2004; Thorell et al., 2009). Therefore I suggest that, when feasible, future studies use the predictive value of neuroimaging studies to consider the overlap. Subsequently, imaging techniques can be used to assess volumetric increases in brain regions associated with the training task (Lustig et al., 2009) as proficient jugglers show an increase in gray matter produced by training compared to non-expert jugglers (Draganski et al., 2004). Another noteworthy but not sufficiently explored technique is the use of transcranial random noise stimulation (tRNS), a non-invasive brain stimulation that is known to facilitate plasticity by activating neuronal populations involved with a certain task. A study employing this technique found an 18% increase in performance after training their participants on a number discrimination task, however, the gain was doubled when the training was accompanied by tRNS. Additionally, the improvements were more long-lasting and transferred to other tests that required quantity judgment (Cappelletti et al., 2013), precisely what is desired from a successful training paradigm.

A second point for future training studies might be to monitor the level of engagement. Having outlined the importance of complexity and motivation for generalization, it is remarkable that most training paradigms seem to not consider engaging their participants, with some studies even being described as boring

(Ackerman et al., 2010; Owen et al., 2010). Using simple measures of arousal (e.g. heart- and breathing rate, skin conductance) it would be possible to investigate and quantify the engagement level of participants, searching for an optimal level of engagement. Motivation itself can largely be controlled by two factors: the adaptiveness of the paradigm and the amount and type of feedback offered on performance. Although most studies include some sort of performance dependent feedback, the types of feedback are inconsistent and only a few studies have directly investigated the role of feedback in learning. One study that directly manipulated the availability of feedback demonstrated that, although direct feedback (after each trial) leads to faster skill acquisition, retention was better in the group that received *summarized* feedback (after 5 or 15 trials) (Schmidt, Young, Swinnen & Shaprio, 1989). One possible explanation is that subjects might get dependent on the availability of feedback, that when this is removed in a retention test, this has negative consequences for their performance since no stable learning was present during the acquisition block.

Thirdly, variability should and can be introduced by considering changes to the task design, and in particular the way conditions are set up. Depending on the goal of the study, experiments can be set up either in blocked design with sequential trials for each given task, or a random order of all possible tasks intermixed. If the aim is to create a direct advantage on the trained task, a block designed is the preferred options. A probable explanation for this advantage is the lack of exposure from interfering trials, allowing for practice on successive trials. However, using a mixed design will result in a more general learning effect. Although not many laboratory-based experiments seem to pay attention to the importance of variability, results from dual-tasking training study on elderly underline the idea that variety leads to increased performance in untrained task conditions (Bherer et al., 2005; Craik et al., 2007; Winocur & Craik, 2007). Furthermore, attention needs to be given to the duration and spacing of training. 60 minute practice sessions which are relatively spread out have lead to stronger long-term retention (Schmidt & Bjork, 1992), but the sparseness of the evidence makes the ideal duration and spacing of training one of the issues to be solved concerning training.

In conclusion, I certainly believe that cognitive enhancement can be achieved by the use of training tasks. Future research therefore should not focus on the effectiveness of training, but must systematically implement the aforementioned suggestions to investigate what training conditions results in the most long-lasting and general learning effects and who are the most suitable candidates for these paradigms. Currently, the large variability in approaches that is seen in the current literature makes it difficult, if not impossible, to make any definitive statements about the workings of transferability or training generalization. I strongly believe in the promising potential of video game training to improve cognitive, motor and executive skills and I think that future research should look into the effectiveness of athletic and musical training as alternatives, given the shared need for high parallel processing across domains in both video games and sports. Preliminary studies have shown that older adults who were made to walk regularly performed better in various tests of executive functioning compared to a control group (Erickson & Kramer, 2009). Lastly, even though the market of commercialized *brain training* is ever expanding, very few studies have empirically shown the value of the employed training in healthy populations. I believe I have outlined some of the factors that seem to be crucial to the success of a training paradigm. By using adaptive paradigms that are tailored to the individual to ensure an optimal complexity, variety and engagement, chances of the trained skill flowing to an untrained task are highest.

REFERENCES

Achtman, R. L., Green, C. S., & Bavelier, D. (2008). Video games as a tool to train visual skills. *Restorative Neurology and Neuroscience*, *26*(4-5), 435–46.

Ackerman, P. L., Kanfer, R., & Calderwood, C. (2010). Use it or lose it? Wii brain exercise practice and reading for domain knowledge. *Psychology and Aging*, *25*(4), 753–66.

Ahissar, M., & Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning. *Trends in Cognitive Sciences*, *8*(10), 457–64.

Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychology and Aging*, *23*(4), 765–77.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2005). Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychology and Aging*, *20*(4), 695–709.

Bjork, E., & Bjork, R. (2011). Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning. *Psychology and the Real World: Essays …*, 55–64.

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control. *Acta Psychologica*, *129*(3), 387–98.

Brehmer, Y., Li, S.-C., Müller, V., von Oertzen, T., & Lindenberger, U. (2007). Memory plasticity across the life span: uncovering children's latent potential. *Developmental Psychology*, *43*(2), 465–78.

Brehmer, Y., Li, S.-C., Straube, B., Stoll, G., von Oertzen, T., Müller, V., & Lindenberger, U. (2008). Comparing memory skill maintenance across the life span: preservation in adults, increase in children. *Psychology and Aging*, *23*(2), 227–38.

Calero, M. D., & Navarro, E. (2007). Cognitive plasticity as a modulating variable on the effects of memory training in elderly persons. *Archives of Clinical Neuropsychology : The Official Journal of the National Academy of Neuropsychologists*, *22*(1), 63–72.

Cappelletti, M., Gessaroli, E., Hithersay, R., Mitolo, M., Didino, D., Kanai, R., … Walsh, V. (2013). Transfer of cognitive training across magnitude dimensions achieved with concurrent brain stimulation of the parietal lobe. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *33*(37),

Cattell, R. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology*, (1), 1–22.

Cavallini, E., Pagnin, A., & Vecchi, T. (2003). Aging and everyday memory: the beneficial effect of memory training. *Archives of Gerontology and Geriatrics*, *37*(3), 241–257.

Cohen, J. E., Green, C. S., & Bavelier, D. (2007). Training visual attention with video games: Not all games are created equal. *Computer games and adult learning*, 205-227.

Conway, A. R. a., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences*, *7*(12), 547–552.

Craik, F. I. M., Winocur, G., Palmer, H., Binns, M. a, Edwards, M., Bridges, K., … Stuss, D. T. (2007). Cognitive rehabilitation in the elderly: effects on memory. *Journal of the International Neuropsychological Society : JINS*, *13*(1), 132–42.

Crossman, E. R. (1959). A Theory Of The Acquisition Of Speed-Skill. *Ergonomics*, *2(2)*, 153-166.

Dahlin, E., Neely, A. S., Larsson, A., Bäckman, L., & Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. *Science (New York, N.Y.)*, *320*(5882), 1510–2.

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: Changes in grey matter induced by training. *Nature*, *427*(6972), 311–312.

Digital Brain Health Market Report: Assess, Enhance Cognition I SharpBrains. (2013). *SharpBrains*. http://sharpbrains.com/executive-summary/

Edin, F., Klingberg, T., Johansson, P., McNab, F., Tegnér, J., & Compte, A. (2009). Mechanism for top-down control of working memory capacity. *Proceedings of the National Academy of Sciences* , *106* (16), 6802–6807.

Erickson, K. I., & Kramer, a F. (2009). Aerobic exercise effects on cognitive and neural plasticity in older adults. *British Journal of Sports Medicine*, *43*(1), 22–4.

Ericsson, K. A., & Lehmann, A. C. (1996). Expert and exceptional performance: evidence of maximal adaptation to task constraints. *Annual Review of Psychology*, *47*, 273–305.

Fahle, M. (2004). Perceptual learning : A case for early selection, 879–890.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science*, *18*(10), 850–5.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*(6939), 534–7.

Green, C. S., & Bavelier, D. (2006). Enumeration versus multiple object tracking: the case of action video game players. *Cognition*, *101*(1), 217–45.

Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological Science*, *18*(1), 88–94.

Green, C. S., & Bavelier, D. (2008). Exercising your brain: a review of human brain plasticity and training-induced learning. *Psychology and Aging*, *23*(4), 692–701.

Holmes, J., Gathercole, S. E., Place, M., Dunning, D. L., Hilton, K. A., & Elliott, J. G. (2010). Working memory deficits can be overcome: Impacts of training and medication on working memory in children with ADHD. *Applied Cognitive Psychology*, *24*(6), 827–836.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(19), 6829–33.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(25), 10081–6.

Jonides, J. (2004). How does practice makes perfect? *Nature Neuroscience*, *7*(1), 10–1.

Kirchner, W. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology*, (4).

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences*, *14*(7), 317–24.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlström, K., … Westerberg, H. (2005). Computerized training of working memory in children with ADHD--a randomized, controlled trial. *Journal of the American Academy of Child and Adolescent Psychiatry*, *44*(2), 177–86.

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Increased brain activity in frontal and parietal cortex underlies the development of visuospatial working memory capacity during childhood. *Journal of Cognitive Neuroscience*, *14*(1), 1–10.

Kuwajima, M., & Sawaguchi, T. (2010). Similar prefrontal cortical activities between general fluid intelligence and visuospatial working memory tasks in preschool children as revealed by optical topography. *Experimental Brain Research*, *206*(4), 381–97.

Levine, B., Stuss, D. T., Winocur, G., Binns, M. a, Fahy, L., Mandic, M., … Robertson, I. H. (2007). Cognitive rehabilitation in the elderly: effects on strategic behavior in relation to goal management. *Journal of the International Neuropsychological Society : JINS*, *13*(1), 143–52.

Lustig, C., Shah, P., Seidler, R., & Reuter-Lorenz, P. a. (2009). Aging, training, and the brain: a review and future directions. *Neuropsychology Review*, *19*(4), 504–22.

Mackrous, I., & Proteau, L. (2007). Specificity of practice results from differences in movement planning strategies. *Experimental Brain Research*, 181–193.

Mahncke, H. W., Connor, B. B., Appelman, J., Ahsanuddin, O. N., Hardy, J. L., Wood, R. a, … Merzenich, M. M. (2006). Memory enhancement in healthy older adults using a brain plasticity-based training program: a randomized, controlled study. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(33), 12523–8.

Miller, G. A. (1956). The Magical Number Seven. *The Psychological Review*.

Morrison, A. B., & Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychonomic Bulletin & Review*, *18*(1), 46–60.

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience*, *7*(1), 75–9.

Owen, A. M., Hampshire, A., Grahn, J. a, Stenton, R., Dajani, S., Burns, A. S., … Ballard, C. G. (2010). Putting brain training to the test. *Nature*, *465*(7299), 775–8.

Rebok, G. W., Carlson, M. C., & Langbaum, J. B. S. (2007). Training and maintaining memory abilities in healthy older adults: traditional and novel approaches. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *62 Spec No*(I), 53–61.

Redding, G. M., & Wallace, B. (2006). Generalization of prism adaptation. *Journal of Experimental Psychology. Human Perception and Performance*, *32*(4), 1006–22.

Rohde, T. E., & Thompson, L. A. (2007). Predicting academic achievement with cognitive ability. *Intelligence*, *35*(1), 83–92.

Saffell, T., & Matthews, N. (2003). Task-specific perceptual learning on speed and direction discrimination. *Vision Research*, *43*(12), 1365–1374.

Sagi, D., & Tanne, D. (1994). Perceptual learning: learning to see. *Current Opinion in Neurobiology*, *4*(2), 195–9.

Schmidt, R. a., & Bjork, R. a. (1992). New Conceptualizations of Practice: Common Principles in Three Paradigms Suggest New Concepts for Training. *Psychological Science*, *3*(4), 207–217.

Schmiedek, F., Lövdén, M., & Lindenberger, U. (2010). Hundred Days of Cognitive Training Enhance Broad Cognitive Abilities in Adulthood: Findings from the COGITO Study. *Frontiers in Aging Neuroscience*, *2*(July), 1–10.

Shing, Y. L., Werkle-Bergner, M., Li, S.-C., & Lindenberger, U. (2008). Associative and strategic components of episodic memory: a life-span dissociation. *Journal of Experimental Psychology. General*, *137*(3), 495–513.

Sims, V. K., & Mayer, R. E. (2002). Domain specificity of spatial expertise: the case of video game players. *Applied Cognitive Psychology*, *16*(1), 97–115.

St Clair-Thompson, H., Stevens, R., Hunt, A., & Bolder, E. (2010). Improving children's working memory and classroom performance. *Educational Psychology*, *30*(2), 203–219.

Suter, E., Marti, B., & Gutzwiller, F. (1994). Jogging or walking—Comparison of health effects. *Annals of Epidemiology*, *4*(5), 375–381.

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science*, *12*(1), 106–13.

Vygotsky, L. S. (1978). Interaction between learning and development (M. Lopez- Morillas, Trans.). In M. Cole, V. John-Steiner, S. Scribner, & E. Souberman (Eds.), *Mind in society: The development of higher psychological processes* (pp. 79– 91). Cambridge, MA: Harvard University Press.

Westerberg, H., Jacobaeus, H., Hirvikoski, T., Clevberger, P., Ostensson, M.-L., Bartfai, a, & Klingberg, T. (2007). Computerized working memory training after stroke--a pilot study. *Brain Injury : [BI]*, *21*(1), 21–9.

Willis, S. L., Tennstedt, S. L., Marsiske, M., Ball, K., Elias, J., Koepke, K. M., … Wright, E. (2006). Long-term effects of cognitive training on everyday functional outcomes in older adults. *JAMA : The Journal of the American Medical Association*, *296*(23), 2805–14.

Winocur, G., & Craik, F. (2007). Cognitive rehabilitation in the elderly: Overview and future directions. *Journal of the International Neuropsychological Society*, *13*, 166–171.