Åbo Akademi

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Training executive functions in the laboratory and in real life:

Cognitive consequences of computer-based exercises and bilingualism

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To my mom

for always being there for me,

no matter what.

TABLE OF CONTENTS

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SVENSK SAMMANFATTNING

Frågan om huruvida de exekutiva funktionerna går att träna och vilken effekt en sådan träning har på relaterade kognitiva funktioner, har väckt stort forskningsintresse. Även om ett betydande antal studier har undersökt detta, är frågan fortfarande obesvarad.

Målet för denna avhandling har varit att undersöka två mycket olika typer av träning av de exekutiva funktionerna: laboratoriebaserad, datoriserad träning (Studie I-III) och träning i det verkliga livet genom tvåspråkighet (Studie IV-V). Att tvåspråkighet skulle fungera som en form av träning av de exekutiva funktionerna baserar sig på idén att hantering av två språk kräver exekutiva resurser och tidigare forskning har visat att tvåspråkighet ger en fördel i de exekutiva funktionerna. Denna avhandling fokuserade på tre exekutiva funktioner: uppdatering av arbetsminnesinnehåll, inhibering av irrelevant information och mental flexibilitet.

I **Studie I-III** undersöktes effekterna av datoriserad träning av uppdatering av arbetsminnet (Studie I), inhibering (Studie II) och flexibilitet (Studie III) hos unga friska vuxna. Resultaten ur alla studier tydde på att prestationen i den tränade uppgiften blir bättre efter träning. Viktigare är ändå att resultaten ur Studie I och II påvisade en förbättring i en uppgift som inte hade tränats, men som mätte den tränade funktionen (nära transfer). I ingen av dessa tre studier resulterade träningen emellertid i en förbättring av prestationen i en otränad uppgift som mätte en annan kognitiv funktion än den som hade tränats (avlägsen transfer). I Studie I användes dessutom PET för att undersöka effekterna av arbetsminnesträning på dopamin, som är en signalsubstans nära relaterad till arbetsminnet. PET-resultaten visade en ökad utsöndring av dopamin i striatum under uppdatering av arbetsminnet till följd av träning.

I **Studie IV** undersöktes förmågan att inhibera irrelevant information i dikotiskt lyssnande hos två- och enspråkiga personer. Resultaten antydde att de tvåspråkiga var bättre på att inhibera den irrelevanta informationen än de enspråkiga var. I Studie V introducerades ett nytt sätt att studera fördelen i de exekutiva funktionerna hos tvåspråkiga och de underliggande mekanismerna hos denna fördel. För att kringgå de metodologiska problemen relaterade till ett upplägg med naturliga grupper, fokuserade detta tillvägagångssätt enbart på tvåspråkiga och undersökte om individuella skillnader i tvåspråkigt beteende hängde ihop med prestationen i exekutiva uppgifter. I studien användes de tre ovannämnda exekutiva funktionerna. Resultaten visade att mer frekventa språkbyten var relaterade till bättre förmåga till mental flexibilitet och ju tidigare en person hade lärt sig det andra språket, desto bättre var förmågan att inhibera irrelevant information.

Sammanfattningsvis tyder resultaten ur denna avhandling på att datoriserad träning av de exekutiva funktionerna kan förbättra prestationen i den tränade uppgiften och i nära relaterade uppgifter, men leder inte till en mer allmän förbättring av kognitiva funktioner. Vidare visar hjärnavbildningsresultaten att arbetsminnesträning modulerar dopamintransmissionen i striatum, vilket tyder på en neural plasticitet i detta signalsubstanssystem till följd av träning. När det gäller tvåspråkighet stöder resultaten idén om att tvåspråkighet har en positiv effekt på de exekutiva funktionerna. Utöver detta erbjuder det nya tillvägagångssättet att undersöka tvåspråkighetens effekt på de exekutiva funktionerna, ledtrådar gällande vilka aspekter av det tvåspråkiga beteendet som kan vara relaterade till fördelen i de exekutiva funktionerna hos tvåspråkiga individer.

ABSTRACT

The question of the trainability of executive functions and the impact of such training on related cognitive skills has stirred considerable research interest. Despite a number of studies investigating this, the question has not yet been solved.

The general aim of this thesis was to investigate two very different types of training of executive functions: laboratory-based computerized training (Studies I-III) and real-world training through bilingualism (Studies IV-V). Bilingualism as a kind of training of executive functions is based on the idea that managing two languages requires executive resources, and previous studies have suggested a bilingual advantage in executive functions. Three executive functions were studied in the present thesis: *updating* of working memory (WM) contents, *inhibition* of irrelevant information, and *shifting* between tasks and mental sets.

Studies I-III investigated the effects of computer-based training of WM updating (Study I), inhibition (Study II), and set shifting (Study III) in healthy young adults. All studies showed increased performance on the trained task. More importantly, improvement on an untrained task tapping the trained executive function (near transfer) was seen in Study I and II. None of the three studies showed improvement on untrained tasks tapping some other cognitive function (far transfer) as a result of training. Study I also used PET to investigate the effects of WM updating training on a neurotransmitter closely linked to WM, namely dopamine. The PET results revealed increased striatal dopamine release during WM updating performance as a result of training.

Study IV investigated the ability to inhibit task-irrelevant stimuli in bilinguals and monolinguals by using a dichotic listening task. The results showed that the bilinguals

exceeded the monolinguals in inhibiting task-irrelevant information. **Study V** introduced a new, complementary research approach to study the bilingual executive advantage and its underlying mechanisms. To circumvent the methodological problems related to natural groups design, this approach focuses only on bilinguals and examines whether individual differences in bilingual behavior correlate with executive task performances. Using measures that tap the three above-mentioned executive functions, the results suggested that more frequent language switching was associated with better set shifting skills, and earlier acquisition of the second language was related to better inhibition skills.

In conclusion, the present behavioral results showed that computer-based training of executive functions can improve performance on the trained task and on closely related tasks, but does not yield a more general improvement of cognitive skills. Moreover, the functional neuroimaging results reveal that WM training modulates striatal dopaminergic function, speaking for training-induced neural plasticity in this important neurotransmitter system. With regard to bilingualism, the results provide further support to the idea that bilingualism can enhance executive functions. In addition, the new complementary research approach proposed here provides some clues as to which aspects of everyday bilingual behavior may be related to the advantage in executive functions in bilingual individuals.

ABBREVIATIONS

BDI	Beck Depression Inventory
BP	Binding potential
BSWQ	Bilingual Language Switching Questionnaire
DA	Endogenous dopamine
DL	Dichotic listening
EF	Executive functions
FL	Forced-left attention condition
fMRI	Functional magnetic resonance imaging
FR	Forced-right attention condition
L2	Second language
LE	Left ear
LEA	Left-ear advantage
LI	Laterality index
NF	Non-forced attention condition
MRI	Magnetic Resonance Imaging
PET	Positron Emission Tomography
RE	Right ear
REA	Right-ear advantage
ROI	Region of interest
RT	Reaction time
SES	Socioeconomic status
WAIS-III	Wechsler Adult Intelligence Scale – Third Edition
WCST	Wisconsin Card Sorting Test
WM	Working memory

1 INTRODUCTION

The question of whether cognitive functions can be improved through training has been a hot research topic during the last decade (for recent reviews, see e.g., Green & Bavelier, 2008; Klingberg, 2010; Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010; Morrison & Chein, 2011). The trainability of *executive functions* (EF) has stirred particular interest, because they represent general high-level control functions that are involved in a great number of mental activities and thus of particular importance to cognitive performances. Also, the clinical potential of executive training and rehabilitation is considerable given the occurrence of executive dysfunction in a wide range of conditions (for a review, see e.g., Lezak, Howieson, & Loring, 2004). Besides computer-based systematic training where people perform executive training tasks, it has been claimed that certain everyday cognitive tasks, such as the use of two languages in bilinguals, can enhance EF (for reviews, see e.g., Adesope, Lavin, Thompson, & Ungerleider, 2010; Bialystok, Craik, & Luk, 2012). Accordingly, the present thesis examines the executive effects of both computer-based short-term training in the laboratory and real-world long-term training through bilingualism.

From the training and rehabilitation perspective, it is usually not interesting to improve performance on the trained task per se, but to improve performance on other untrained tasks, elicit general improvement in related skills, and, in the end, increase the quality of everyday life. This encompasses the idea of *transfer*, a concept first studied by Thorndike and Woodworth (1901). Transfer is said to occur when learning in one context affects performance in another context (Salomon & Perkins, 1989). The possible generalization of learning can involve *near transfer*, in other words, transfer between similar contexts, and *far transfer*, which refers to transfer between contexts (Perkins & Salomon, 1992). It has been suggested that transfer can occur either due to *automaticity* or to *mindful abstraction* ('low-road' and 'high-road' transfer in Salomon & Perkins, 1989).

Transfer due to automaticity occurs when a skill or task is practiced until it becomes automatic. Transfer due to mindful abstraction, on the other hand, refers to a deliberate use of for example a strategy or a principle that has been learned in another context. The present thesis mainly aims at transfer due to automaticity. Here, near transfer is defined as generalization to the same cognitive domain (e.g., working memory [WM] training leading to improved performance on another untrained WM task), and far transfer, generalization to another cognitive domain (e.g., WM training leading to improvement on a task measuring inhibition), due to shared components in the tasks.

The concept of EF is still somewhat ill-defined, despite the fact that a number of theories on the organization of EF exist (for reviews, see Banich, 2009; Barkley, 2012; Jurado & Rosselli, 2007). It is thus not clear exactly which functions constitute EF, how they operate, and what the underlying neural mechanisms are (see e.g., Braver, Paxton, Locke, & Barch, 2009; Koechlin & Summerfield, 2007 for theories on the neural basis of EF). Most researchers, however, agree that the prefrontal cortex plays a critical role in EF (for a review, see Banich, 2009). The lack of clarity regarding the construct of EF makes it a challenge to study. For this thesis, three commonly postulated components of EF were chosen. Based on studies of the psychometric relationships between tasks that are often used to assess EF, Miyake and his colleagues (Friedman & Miyake, 2004; Miyake et al., 2000) have suggested that there are three major separable but strongly interrelated EF: *updating* (and monitoring) of WM representations, *inhibition* of unwanted responses, and *shifting* between tasks and mental sets. This tripartite division is adopted in the present thesis work.

1.1 Working memory updating

WM is a central construct in psychology (for a review, see e.g., Conway et al., 2005), referring to a capacity-limited, multicomponent system responsible for maintaining and manipulating information in the face of ongoing processing (Baddeley, 2000). Several studies have shown that WM performance is related to performance on tasks measuring other cognitive functions, such as general fluid intelligence (for reviews, see e.g., Engle, 2002; Shipstead, Redick, & Engle, 2010). In situations where the stream of information exceeds WM capacity, WM updating is required (Szmalec, Verbruggen, Vandierendonck, & Kemps, 2011). WM updating refers to the ability to replace old information with new, more relevant, information (Miyake et al., 2000).

WM updating is often measured with running memory spans. In these tasks, sequences of items (e.g., letters) are presented and when a sequence ends, the task is to recall a given number of the last items presented (e.g., Broadway & Engle, 2010; Bunting, Cowan, & Saults, 2006). The lengths of the presented sequences are unpredictable. Another WM updating task that is commonly used in research is the *n-back* task. In this task, the participants are presented with a list of items (e.g., letters) and the task is to determine whether each item matches the one presented *n* trials back. This requires constant updating of the stream of information in WM, as the task proceeds and new items are presented (e.g., Szmalec et al., 2011).

Most of the evidence of the trainability of EF stems from WM training studies. Several studies have reported either near or far transfer, or both, as a result of training (Brehmer, Westerberg, & Bäckman, 2012; Salminen, Strobach, & Schubert, 2012; for recent reviews, see Klingberg, 2010; Melby-Lervåg & Hulme, 2012, Morrison & Chein, 2011; Shipstead et al., 2010; Shipstead et al., 2012). In fact, based on the promising results from WM training studies, several commercial, computerized WM training programs have been developed in recent years for people with different kinds of cognitive problems (for a review, see Melby-Lervåg & Hulme, 2012). There is, however, still much controversy regarding the effects of WM training, which will be discussed below (section 1.4).

With regard to the neural underpinnings, previous research has shown that WM performance is related to activation of a widespread fronto-parietal network (for a review, see Rottschy et al., 2012). Furthermore, considerable evidence suggests a connection between the dopaminergic system and WM (for e review, see Cropley, Fujita, Innis, & Nathan, 2006). More specifically, computational models have linked striato-frontal dopaminergic activity to a selective gating function in WM. Based on these models, dynamic changes in the level of dopamine switches the system between updating and maintenance and thereby opens and closes the gate for incoming information. Maintenance has been related to D1 receptor activity and updating to D2 receptor activity. D1 receptors are extrasynaptic and respond to lower levels of dopamine, while D2 receptors are mainly located in the synapses and respond only to high levels of dopamine. Thus, a phasic burst of dopamine will open the gate and result in WM updating (for a review, see O'Reilly, 2006). Given the central role of striatal systems in WM updating, one would expect to see changes in these regions following successful WM updating training. Indeed, Dahlin, Neely, Larsson, Bäckman, and Nyberg (2008) showed by functional magnetic resonance imaging (fMRI) increased task-related blood flow in the left striatum after WM training, but this method does not allow to link this change directly to dopamine. Using positron emission tomography (PET), McNab et al. (2009) reported changes in cortical dopamine receptor (D1) density following WM training, but their data were obtained from resting state measurements and do not provide direct evidence for a training-related change in endogenous dopamine release during WM updating.

1.2 Inhibition

Inhibition can be considered a subcomponent of attentional control (e.g., Jurado & Rosselli, 2007) and refers to the ability to deliberately suppress dominant responses

(Miyake et al., 2000). There are several ways to measure inhibition, but one of the tasks used in the present thesis is the forced-attention dichotic listening (DL) task (e.g., Hugdahl & Andersson, 1986).

In this task, different consonant-vowel syllables are simultaneously presented to the left and the right ear. In the non-forced (NF) condition, the task is to report the stimulus heard best, irrespective of ear. In the forced-right (FR) condition, the participant is instructed to report only stimuli that are presented to the right ear and inhibit stimuli that are simultaneously presented to the left ear. Finally, in the forced-left (FL) condition, the participant is instructed to report only the left-ear stimuli and inhibit those presented to the right ear. It is usually easier for healthy right-handed individuals to report speech sounds presented to the right than to the left ear, yielding a right-ear advantage (REA) in the NF condition. As the contralateral auditory projections are stronger than the ipsilateral ones, the REA reflects left temporal lobe specialization for speech sound processing (Hugdahl, 2000; Kimura, 1967). The forced-attention conditions, however, engage attentional processes which can modulate the REA effect (e.g., Gadea et al., 2002; Gootjes et al., 2006). The FR condition increases the REA, whereas the FL condition decreases the REA to some degree (although not to the same extent as the FR condition increases the REA), often yielding a left-ear advantage (LEA) in healthy right-handed adults (e.g., Andersson, Reinvang, Wehling, Hugdahl, & Lundervold, 2008; Takio et al., 2009; Thomsen, Rimol, Ersland, & Hugdahl, 2004).

To the best of the author’s knowledge, only a handful of studies have addressed training of inhibition or attentional control at large. A study with healthy older adults (Mozolic, Long, Morgan, Rawley-Payne, & Laurienti, 2011) showed both near and far transfer as a result of training of attentional control. Studies with children, on the other hand, have shown far but no near transfer (Rueda, Rothbart, McCandliss, Saccomanno,

& Posner, 2005), or no transfer at all (Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009). Further, regarding training specifically with the DL task, preliminary evidence suggests that at least in children with auditory processing deficits, who demonstrate a significant interaural asymmetry due to poorer left-ear DL performance, it is possible to achieve even long-lasting effects on DL performance through training, with concomitant changes in receptive language abilities (Moncrieff & Wertz, 2008).

1.3 Set shifting

Set shifting (or task switching) refers to the ability to switch between tasks or mental sets (Miyake et al., 2000). Set shifting is usually measured with setups that include two or more simple classification tasks (e.g., classifying numbers as even or odd and classifying letters as vowels or consonants) in the same task sequence. The sequence includes occasional shifts from one classification principle to another, providing measures for the cognitive cost of switching (Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010). One commonly used set shifting task is the Wisconsin Card Sorting Test (WCST), a complex executive task that taps particularly set shifting, but also attentional control and WM (Lie, Specht, Marshall, & Fink, 2006), as well as other cognitive processes such as abstract reasoning, strategic planning, problem-solving, and organized search (see e.g., Heaton, Chelune, Talley, Kay, & Curtiss, 1993). In this task, the participant is asked to match response cards with four stimulus cards, based on sorting rules (color, form, and number of symbols) that keep changing during the task sequence.

Only two studies have been conducted on training of set shifting and its possible transfer effects. The results from these studies indicate both near transfer (Karbach & Kray, 2009; Minear & Shah, 2008) and far transfer to inhibition, verbal and spatial WM, and fluid intelligence (Karbach & Kray, 2009) as a result of set shifting training.

1.4 Transfer or no transfer?

To summarize, there is great variability between studies regarding training outcome, as studies report near transfer, far transfer, both near and far transfer, and no transfer at all as a result of training of EF (for a review, see e.g., Green & Bavelier, 2008). Furthermore, after the present studies were conducted, a meta-analysis (Melby-Lervåg & Hulme, 2012) and some recent reviews (Morrison & Chein, 2011; Shipstead et al., 2010; Shipstead, Redick, & Engle, 2012) have pointed out that the results from previous WM training studies may have been confounded by methodological shortcomings, such as employing a no-contact control group, of not randomly assigning participants to groups, and of using only one task to measure an entire cognitive ability (note that the same methodological criticisms could be extended also to studies on the trainability of other EF). Melby-Lervåg and Hulme (2012), in fact, showed that WM training can produce immediate near transfer effects on WM skills, but that these improvements do not persist long-term. Their meta-analysis showed no reliable evidence for far transfer as a result of WM training. Nevertheless, a better controlled recent study reports both near and far transfer of WM training (Brehmer et al., 2012). To what extent training of EF can generalize to untrained tasks, is thus a question that remains unanswered.

1.5 Bilingualism as real-world training of executive functions

The effects of bilingualism on cognitive functions have stirred research interest for many decades and several group studies comparing monolingual and bilingual individuals (both children and adults) have shown a bilingual advantage in various executive tasks, particularly measuring inhibition, but also set shifting and WM (for reviews see e.g., Adesope et al. 2010; Bialystok, 2009; Bialystok, Craik, & Luk, 2012; Hilchey & Klein, 2011).

The exact source of the bilingual advantage in EF is not clear, but it is thought to stem from the fact that managing two languages requires executive resources for selecting the relevant language and inhibiting the language not in use at that moment (Abutalebi & Green, 2007; Bialystok, Craik, Green, & Gollan, 2009; Green, 1998; Meuter & Allport, 1999; Moreno, Rodríguez-Fornells, & Laine, 2008; Rodriguez-Fornells, De Diego Balaguer, & Münte, 2006; Ye & Zhou, 2009). Recently, it has been suggested that the bilingual advantage in EF stems from better conflict-monitoring (i.e., monitoring the different languages that compete for selection), and not from pure inhibition of the language not in use at that moment (Hilchey & Klein, 2011). Since bilinguals have a lifelong experience in controlling their two languages, they should have received more practice than monolinguals in processes that engage EF. Bilingualism would, according to this idea, serve as a kind of real-world training of EF.

Stocco, Yamasaki, Natalenko, and Prat (2012) recently linked the idea of bilingualism as "brain training" to their neurocognitive model of skill acquisition. According to this model, coined as the Conditional Routing Model, language switching (selection of appropriate language and representation) and EF (set shifting and control over competing information) engage the same basal ganglia circuitry. In this model, the basal ganglia and particularly the striatum are seen as a gating system for information going to the prefrontal cortex. The model thus assumes that the bilingual advantage in EF stems from extensive language-switching practice which enhances the ability of the basal ganglia to control, route, and override signals from other cortical areas to the prefrontal cortex. Based on this model, one could assume that bilingualism would train the brain in a similar manner as systematic laboratory-based training of EF (see also Abutalebi et al., 2012). Interestingly, it has also been suggested that bilingualism as lifelong training would create a cognitive reserve (similar to higher education or IQ; Tucker & Stern, 2011) that may protect against cognitive decline and even postpone symptoms of dementia (Bialystok, Craik, & Freedman, 2007; Craik, Bialystok, & Freedman, 2010; for a review, see Bialystok et al., 2012).

2 AIMS AND RESEARCH QUESTIONS

The general aim of the present thesis was to study to what extent WM updating, inhibition, and set shifting can be trained in healthy adults, either through computerized short-term training in the laboratory or through lifelong practice in being a bilingual. The specific aims of the five studies were as follows:

Computer-based training of executive functions

Study I. To investigate whether WM updating training affects striatal DA release in healthy young adults during WM updating performance. The aim was also to study possible behavioral transfer effects of WM updating training.

Study II. To investigate to what extent DL-training can affect the ability to inhibit irrelevant information in healthy young adults and to explore whether the training effects transfer to untrained cognitive tasks. The aim was also to compare the effects of top-down (instruction-driven) and bottom-up (stimulus-driven) DL-training (see section 4.1.2 for a description of the different training regimes). We expected to see training-related effects especially following top-down training, as it might be easier to influence high-level control processes than the basic perceptual bottom-up processes with just a few weeks' intervention.

Study III. To explore the effects of set shifting training in healthy young adults and to investigate to what extent the training gains transfer to other tasks. The aim was also to compare the effects of predictable and unpredictable set shifting training. We hypothesized that the cognitively more demanding practice of unpredictable set shifting should elicit more pronounced training gains.

Bilingualism as real-world training of executive functions

Study IV. To test a hypothesis put forth by Hugdahl et al. (2009) that bilinguals would show an advantage in forced-attention DL due to better inhibition skills. The aim was also to compare possible effects of bilingualism on inhibition performance in younger and older adults.

Study V. To introduce a new complementary multiple regression approach to study the bilingual advantage in EF and its underlying mechanisms. This approach focuses solely on bilinguals and attempts to predict variability in executive measures by self-estimated features of bilingual behavior such as the frequency of language switches in everyday life.

3 PARTICIPANTS

In all studies, the participants (Table 1) were asked to give their written informed consent and to fill out the Edinburgh Handedness Inventory (Oldfield, 1971). They also completed a background information sheet probing for example their age, education, occupation, possible reading difficulties, possible neurological and psychiatric illnesses, medication, and level of alertness.

3.1 Computer-based training of executive functions

3.1.1 Study I

This study employed 20 Finnish, right-handed, male university students (M_{age} = 22.3 years, *SD* = 3.1). According to self-reports, the participants were not on any medication (allergy medicine excluded), had no drug or alcohol abuse, did not use any nicotine products, and had not taken part in a PET-study previously. The participants were randomly divided into a training (n = 10) and a control group (n = 10). These two groups were comparable in age and neuropsychological performance.

3.1.2 Study II

The participants consisted of 50 right-handed university students (M_{age} = 23.5 years, *SD* = 3.3). All participants had normal hearing acuity. The participants were randomly divided into four groups: (a) the bottom-up group (n = 10), (b) the top-down group (n = 10), (c) the bottom-up + top-down group (n = 20), and (d) the control group (n = 10), all comparable in age and sex ratio.

3.1.3 Study III The participants consisted of 42 right-handed, Finnish university students (M_{age} = 23.4 years, *SD* = 2.3). The participants were matched within triads according to their pretraining set shifting performance (uncued categorization; see section 4.3 for task details) and based on this, randomly divided into three groups: (a) the cued training group (n = 14), (b) the uncued training group (n = 14), and (c) the control group (n = 14), all comparable in age and sex ratio.

3.2 Real-world training of executive functions

3.2.1 Study IV

The study employed two age groups of right-handed Finnish monolinguals and early (i.e., they had learned both languages before the age of 7 and since then actively used them throughout their lives) and balanced (i.e., they considered their language skills in both languages to be fluent) Finnish-Swedish bilinguals. The younger group consisted of 18 monolinguals (M_{age} = 38.5 years, *SD* = 6.2) and 17 bilinguals (M_{age} = 40.1 years, *SD* = 6.6), and the older group of 14 monolinguals (M_{age} = 67.6 years, *SD* = 3.9) and 16 bilinguals (M_{age} = 66.0 years, *SD* = 4.0). There was no significant difference in age between monolinguals and bilinguals in the younger or the older group, and the groups were comparable regarding sex ratio and socioeconomic status (SES).

3.2.2 Study V

This study employed 38 early-simultaneous, balanced Finnish-Swedish bilinguals (the same as in Study IV plus five participants excluded from Study IV due to either hearing problems or technical problems with the forced-attention DL task; M_{age} = 52.8 years, *SD* = 15.0).

Table 1

Summary of the Participant Characteristics and an Overview of the Research Questions in the Studies

Study	Research issues	Participants	n	Age in years	M/F
Computer-based training of executive functions					
I	Training WM and the effects on striatal dopamine release	Young adults	10 training group	20-26	all male
			10 control group	19-33	all male
II	Training inhibition	Young adults	10 bottom-up group	20-29	4/6
			10 top-down group	19-28	2/8
			20 bottom-up + top-down group	20-31	3/17
			10 control group	19-25	3/7
III	Training set shifting	Young adults	14 uncued training group	20-30	5/9
			14 cued training group	21-30	8/6
			14 control group	21-27	7/7
Real-world training of executive functions					
IV	Inhibition in bilinguals v. monolinguals	Finnish-Swedish bilinguals and Finnish monolinguals	18 monolinguals	30-49	8/10
			17 bilinguals	30-50	6/11
			14 monolinguals	62-74	4/10
			16 bilinguals	60-73	3/13
V	Bilingual behaviors and EF	Finnish-Swedish bilinguals	38	30-75	12/26

4 METHODS

This chapter gives a brief description of the methods used in the five studies. Studies I-III investigate computer-based training of EF and Studies IV-V real-world training of EF. See Table 2 for a summary of the employed tasks. A more thorough description of the tasks and measures is given in the original studies.

4.1 Computer-based training of executive functions

Computer-based training of EF was investigated in Studies I-III. All studies consisted of a pretest (i.e., a baseline measurement of the skills at interest), an intervention period, and a posttest (i.e., an evaluation of the effects of the intervention on the skills at interest). A control group was employed in all studies.

4.1.1 Study I

Procedure

Before training, all participants underwent a structural magnetic resonance imaging (MRI) scan of the brain and a medical examination. They all took part in pre- and post-PET measurements. In addition to this, pre- and posttestings were administered outside the scanner. The time period between pre- and postsessions was 6-9 weeks, during which the training group received training for 5 weeks, with 3 sessions per week, 45 minutes per session. The control group received no training.

Tasks administered at the pre- and postsessions

The pre- and postsessions included the visual N-back task (WM updating; Cohen et al., 1994), the visuospatial N-back task (WM updating; adapted from Carlson et al., 1998), the Recall of concrete nouns (episodic memory; Dahlin et al., 2008), the Simon task (inhibition; Simon & Rudell, 1967), and the Number-letter task (set shifting; adapted from Rogers & Monsell, 1995). The pre- and postsessions also included the Digit span

(*Wechsler Adult Intelligence Scale – Third Edition* [WAIS-III]; WM), the Letter-number sequencing (WM; WAIS-III), and the Digit symbol (perceptual speed; WAIS-R) subtests. Tests included only in the pretest session were as follows: Pattern comparisons and Number copying (mental speed; Salthouse & Babcock, 1991), Trail Making A and B (visual scanning; Lezak, 1995), Vocabulary (verbal comprehension; WAIS-III), and the Beck Depression Inventory (BDI; Beck, Steer, & Brown, 1996). The pre- and post-PET sessions included the Letter-memory task (WM updating; Dahlin et al., 2008).

The visual N-back task. In this task, numbers from 1 to 9 were presented one at a time at the center of the screen and the task was to remember the previous number (1-back) or the one presented three trials back (3-back), depending on the instructions given. The participant was to press the "yes" key for a *target* (i.e., the number was the same as the previous number/the one three trials back), and the "no" key for a *non-target* (i.e., the number did not match). The dependent measures on this task were the reaction times (RTs) and error rates on 1-back and 3-back trials, separately for targets and non-targets..

The visuospatial N-back task. In this task version, a white square was presented in one of eight possible locations on the screen. The participant was to remember either the location of the previous square (1-back) or the one before the previous square (2-back), depending on the instructions given. The participant pressed the "yes" key each time the square appeared in the same location as the previous square/the one before the previous square, and the "no" key each time the location was different. The dependent measures on this task were the RTs and error rates on 1-back and 2-back trials.

Recall of concrete nouns. In this task, 18 concrete nouns were presented one at a time on the computer screen. The administration of the task followed Buschke's (1973) selective reminding procedure. On the first trial, all nouns were presented and the participant’s task was to immediately recall as many words as possible. On the two subsequent trials, only the nouns that were not recalled on the previous trial were read aloud by the examiner and the participant was again asked to repeat all nouns, both the reminded and the non-reminded ones. The total number of correctly recalled items was used as the dependent measure on this task.

The Simon task. In this task, a blue or a red square appeared on either the left or the right side of the screen. The participants were to push the left button each time a blue square appeared and the right button each time a red square appeared, irrespective of the side the square was presented on. On *congruent* trials, the response button was on the same side as the square and on *incongruent* trials, the square was on the opposite side of the response button, in other words, the irrelevant spatial information was conflicting with the correct response. The RTs and error rates on congruent and incongruent trials were used as the dependent measures.

The Number-letter task. In this task, a number-letter combination (e.g., 3A) appeared in one of two squares at the centre of the screen. The task was to either determine if the number was even or odd or if the letter was a vowel or a consonant, depending on in which square the number-letter pair appeared. The squares thus served as cues for which task to perform. Each time the number-letter combination was in the upper box, the task was to determine the number and each time it appeared in the lower box, the task was to determine the letter. Task switching was unpredictable for the participant, as the number-letter combination appeared in the two squares randomly. The left button was to be pressed each time the number was even or the letter was a vowel, and the right button each time the number was odd or the letter was a consonant. The task consisted of two *single-task blocks* (the stimuli appeared only in the upper box; the stimuli appeared only in the lower box) and one *mixed-task block* (the location of the stimulus alternated), which consisted of *repetition trials* (the stimulus was in the same square on the previous trial) and *switching trials* (the stimulus was in the other square on the previous trial). The dependent measures on this task were mean RTs and error rates (in percent) for single-task trials, repetition trials, and switching trials.

Positron emission tomography imaging

PET is a method used to obtain biochemical information of physiological processes in living organisms. In PET imaging, a biologically active ligand, labeled with a positron-emitting isotope (e.g., 11C, 13N, 15O, or 18F), is administered to the bloodstream of the participant. After administration, the radioactive ligand accumulates to the target tissue for which the molecule has affinity. The radioactive nucleus then decays and results in emission of a positron. When the positron collides with an electron, *annihilation* occurs and energy is emitted. The energy is divided into two photons that are simultaneously emitted in opposite directions and can be detected by the PET scanner, which consists of a ring of detectors. These photon pair detections by the PET scanner are referred to as *coincidence events*, and indicates that an annihilation has occurred somewhere along the line between the detectors. The number of coincidence events between detectors reflects the amount of radioactivity on the line between these detectors (e.g., Analoui, Bronzino, & Peterson, 2012; Turkington, 2001).

PET is a unique technique to measure synaptic transmission in the living brain at a given point in time. The underlying principle behind using PET imaging in investigating the dynamics of the dopamine system is the idea that the dopamine produced by the living organism itself (endogenous dopamine; DA) and the radioligand compete for binding to neuroreceptors. Changes in the synaptic concentration of a neurotransmitter translate into changes in transmitter receptor occupancy that can be detected as changes in the binding potential (BP) of the radioligand. The *occupancy model* predicts that when the synaptic concentration of DA increases in the target tissue (as a result of for example an increased WM load), the binding of DA to dopamine receptors also increases, and results in reduced availability of dopamine receptors for the radioligand, and vice versa (for a review, see Laruelle, 2000). Previous research has established that the radioligand [^{11}C] raclopride competes with DA in a manner predicted by the occupancy model (for a review, see Laruelle, 2000). It has also previously been shown that task-related changes in striatal dopaminergic activity can be revealed by using [^{11}C] raclopride (e.g., Badgaiyan, Fischman, & Alpert, 2007).

We used a brain-dedicated high-resolution ECAT HRRT PET scanner (Siemens Medical Solutions, Knoxville, TN, USA) and [^{11}C] raclopride radioligand with bolus-plus-infusion administration to measure striatal dopamine D2 receptor availability during WM updating v. control task performance. In the bolus-plus-infusion method, half of the [^{11}C] raclopride dose was administered as a bolus, followed by constant infusion of the other half during 105 minutes.

All images were corrected for attenuation, scattering and random events. There were no systematic differences in the subject motion between the control and updating conditions, or between the groups. The PET results were analyzed using region of interest (ROI) analysis and voxel-based methods. ROI delineations were drawn bilaterally in caudate nucleus, putamen, and the cerebellum, on fusion images of PET and MR images.

Cerebellum was used as a reference region in the linearized simplified reference tissue model (LSRTM; see Alpert, Badgaiyan, Livni, & Fischman, 2003) when generating ROI-based and voxel-wise maps of baseline binding potential (BP_{ND}) and standardized value of change (Z-value of γ) in D2 receptor availability during the WM updating task compared to the control task. The $Z(\gamma)$ values were used as the dependent variables for the PET data analysis.

The letter-memory task. In this task, lists of letters from A to D appeared in the center of the computer screen one at a time. Each time a list suddenly ended, the task was to report the four last letters presented by pressing the corresponding response keys. The task consisted of a control condition and an updating condition. In the control condition, all letters in a sequence were the same (e.g., A, A, A, A or C, C, C, C) and in the updating condition, the letters appeared in a mixed randomized order.

The letter-memory updating task used during PET sessions began with the control condition that started 5-10 minutes before the bolus injection and lasted for 55 min after the administration of the bolus. After this, the updating condition began and lasted for 25 minutes. The task then switched back to the control condition which continued until the radioligand infusion was finished, approximately for 25 minutes. The total duration of the task was 110-115 minutes. The dependent measure was the number of correctly reported four-letter sequences.

Training paradigm

The training program was the same computerized adaptive training regime as used by Dahlin et al. (2008). It consisted of the letter-memory task and five other WM updating tasks. During the 5-week training period, the level of difficulty was increased when the participant reached a score of 80 % or higher in the letter-memory task. The letter-memory task used in training included only the WM updating condition and consisted of 10 lists of letters of varying length (5-11 letters). Four of the other training tasks followed the same format as the Letter-memory task, but in order to render the updating training more general, different types of stimuli were used: numbers, letters, colors, and spatial locations. Each task consisted of five lists of stimuli and the participant had to recall the four last presented items in each list. The level of difficulty was manipulated by increasing list length (low level = 4-7 items, medium level = 6-11 items; high level = 5-15 items). All participants reached the highest level during training. The sixth training task was a keep-track task that was structurally somewhat different from the other updating tasks in the training paradigm, but also involved WM updating. The rationale for including the keep-track task was to provide a more general training in WM updating. In this task, lists of 15 words from different semantic categories were presented on the screen. The task was to mentally place each word in the corresponding semantic category (animals, clothes, countries, relatives, sports, and professions) indicated by boxes with the category names at the bottom of the screen. At the end of each list of words, the participants were to type the word that was presented last under each category. The participants thus had to continuously update their WM in order to remember the last word presented in each category. The difficulty level was manipulated by varying the number of categories: three (low level), four (medium level) and five (high level). The training data was not included in the statistical analyses.

Statistical analyses

Regarding the PET data, Statistical Parametric Mapping version 8 (SPM8, Wellcome Trust Centre for Neuroimaging, University College London, UK) and a [^{11}C] raclopride template developed in-house were used to obtain spatial congruity between the individual images for group-wise voxel-level statistical analysis. The data were low-pass filtered by convolving the $Z(\gamma)$ images using a Gaussian kernel with 4 mm FWHM in all three dimensions. Because the images could not be assumed to be normally distributed, non-parametric analyses were conducted using SnPM (http://www.sph.umich.edu/ni-stat/SnPM/). Variance smoothing was used with a

FWHM of 10mm. One thousand permutations were used to determine a $p < .01$ threshold within the restricted striatal search space. The effects of time of testing and group on $Z(\gamma)$ values was studied with a mixed-model ANOVA.

Regarding the behavioral data, a mixed-model ANOVA was performed to study the effects of time of testing and group on Letter-memory performance. Mixed-model ANOVAs were used also for the transfer tasks to compare performance of the groups from pre- to posttest. Statistically significant interactions were studied further with appropriate ANOVAs. Finally, one-way ANOVAs were used to compare groups on the neuropsychological background tests.

4.1.2 Study II

Procedure

All participants were tested before and after the training period. The time period between pre- and postsessions was approximately five weeks, during which all groups received training for 4 weeks, with 4 sessions per week, and 30 minutes per session.

Tasks administered at the pre- and postsessions

The pre- and postsessions included the forced-attention DL task, the Stroop task (inhibition; Stroop, 1935), the auditory-spatial interference task (inhibition; adapted from Pieters, 1981), an auditory go/no-go spatial attention task (selective attention; Takio, Koivisto, Laukka, & Hämäläinen, 2011), and the auditory letter N-back task (WM updating). Digit span (WAIS-III) was included only in the pretest session.

The forced-attention dichotic listening task. This paradigm utilizes phonologically relevant but semantically meaningless consonant-vowel syllables as stimuli. The syllables were presented through headphones, one syllable to the left and one to the right ear. The task consisted of three conditions: the FR, the FL, and the NF condition. In the NF condition, the task was to report the syllable heard best, irrespective of ear. In the FR condition, the participants were instructed to report the syllable presented to the right ear and in the FL condition, the syllable presented to the left ear. The stimulus material consisted of six syllables, created by combining a consonant to the vowel /a/: /ba/, /da/, /ga/, /pa/, /ta/, /ka/. Before training, all participants completed the NF condition with the standard intensity level of 70 dB for both ears. After this, an estimation of the REA threshold was made by adaptively decreasing the right-ear intensity until the participant reported approximately the same number of syllables from the left and the right ear. The FR and the FL conditions were then administered in counterbalanced order with standard intensity levels. The posttraining session consisted of the forced-attention DL task with standard intensity levels. In addition to the number of reported syllables, laterality indices (LI; i.e., the percentage difference between right- and left-ear scores: LI = (RE-LE)/(RE+LE) x 100) were used as dependent measures in this study.

The Stroop task. In this task, the words "blue" and "red" were presented at the center of the screen, written in either red or blue color. The participant was instructed to respond either according to the meaning of the word and to ignore the color (word version), or according to the color irrespective of the meaning of the word (color version). The two versions consisted of both congruent and incongruent trials. On the congruent trials, the word "blue" was written in blue and the word "red" in red. On the incongruent trials, the word "red" was written in blue and vice versa. The dependent variables on this task were RTs on congruent and incongruent trials separately for the color and the word version. The analyses were conducted on RTs only, due to low error rates on this task.

The auditory-spatial interference task. In this task, the words “left” and “right” were presented to either the left or the right ear through headphones. The task was either to give a response based on which ear the word was presented to and to ignore the meaning of the word (side version), or based on the meaning of the word, irrespective of which ear the word was presented to (word version). The two versions consisted of both congruent and incongruent trials. On the congruent trials, the word “left” was always presented to the left ear and the word “right” to the right. On the incongruent trials, the word “left” was presented to the right ear, and vice versa. The dependent variables on this task were RTs on congruent and incongruent trials separately for side and the word version. Due to low error rates, the analyses were conducted on RTs only.

The auditory go/no-go spatial attention task. In this task, two separate streams of digits (1-9) were presented simultaneously to the left and the right ear and the task was to detect target digits. The target digits were “6” and “9” presented to the left ear and “8” and “3” to the right ear. There were two versions of the task. In a slower version, the digits were presented with an interstimulus interval of 200-1000 ms, and in a faster version the interstimulus interval was 150-650 ms. Both versions consisted of trials in which two digits were presented at the same time, one to the left ear and one to the right, and trials in which digits were presented only to one ear. The dependent variables on this task were RTs on dichotically presented targets, and the number of incorrect key presses (pressing only the right or the left key albeit both ears received a target; cf. Hämäläinen & Takio, 2010; Takio et al., 2011) in response to dichotic targets, separately for the slow and the fast version.

The auditory letter N-back task. In this version of the N-back task, a stream of consonants was presented through headphones. The task was to decide if the letter presented was the same as the one heard three letters back, by pressing the “yes” key each time the letter was a target (the same letter as three letters back) and the "no" key whenever it was a non-target. The dependent measures on this task were RTs and error rates.

Training paradigm

The forced-attention DL task was used as the training task in this study. The *bottom-up group* trained the NF condition with bottom-up facilitation (stimulus intensity adjustment) of left-ear reports. The intensity difference between the ears was manipulated to first make left-ear reporting very easy and then gradually more difficult. The initial intensity of the right-ear stimuli was the REA threshold minus 9 dB. It was then increased by 3 dB every week. Thus, at week 4, the intensity was at the REA threshold level. The intensity of the left-ear stimuli was kept constant at 70 dB during the whole training period. The *top-down group* trained on the FL condition throughout the training period, in other words, they were instructed to focus on and report the syllables presented to the left ear and ignore the right-ear stimuli. The stimulus intensity levels were equal for both ears throughout the intervention period. The *bottom-up + top-down group* trained forced-attention DL with bottom-up facilitation, which means repeatedly performing the FL condition with the interaural intensity difference adjusted in the same way as for the bottom-up group. The *control group* performed the NF condition with equal intensities for both ears throughout the whole training period. The training data was not used in the statistical analyses.

Statistical analyses

In this study, we first investigated the comparability of the four groups on their pretraining DL performances. However, the results from a mixed-model ANOVA on the number of reported syllables in each attention condition per ear showed that the groups were, in fact, not balanced on their pretraining DL performances. To control for these differences, mixed-model ANCOVAs with posttraining performance as the dependent variable, and pretraining performance as a covariate were conducted (e.g., Senn, 2006). To study the right- and left-ear response ratios, mixed-model ANCOVAs were conducted on the LI measure separately for the attention conditions, with bottom-up training (applied v. not applied) and top-down training (applied v. not applied) as between-subject factors. Similar ANCOVAs were conducted on the average number of reported syllables, in order to study overall DL performance.

Regarding the transfer tasks, ANOVAs on the pretraining performance revealed no statistically significant group differences. Accordingly, mixed-model ANOVAs were performed to study the effect of type of training and time of testing on performance on the transfer tasks. Statistically significant interactions were studied further with appropriate ANOVAs.

4.1.3 Study III

Procedure

All participants took part in the pre- and postsessions, administered with approximately three weeks apart. Between the pre- and postsessions, the training groups trained for two weeks, three times per week, and 30 minutes per session. The control group received no training.

Tasks administered at the pre- and postsessions

The pre- and postsession consisted of the following six computerized tasks: Digit span (WAIS-III), Raven's Standard Progressive Matrices (fluid intelligence; Raven's SPM; Raven, Raven, & Court, 2004), a categorization task adapted from the WCST (set shifting), the Number-Letter task, the Simon task, and the visual N-back task.

The categorization task. In this task, four different stimulus cards appeared in a horizontal line at the top of the computer screen. The task was to match response cards, appearing one at a time, with the stimulus cards, based on a sorting rule that would change after a varying number of trials. The task employed two difficulty levels. In the easier version, the task was to sort the response cards according to three sorting rules: shape, color, and quantity. Sorting was to be done by deciding which stimulus card had figures of the same shape, color, or number, as the figures on the response cards, based on the sorting rule valid at that moment. In the difficult version of the task, location was added as a fourth sorting rule and feature on the stimulus cards.

In addition, two separate task versions for both difficulty levels were created, namely *cued* and *uncued* presentation of the stimuli. In the cued version, each time the sorting rule was about to change, the new correct sorting rule was given in written form on the computer screen. In the uncued version, no cues of the sorting rules were given, meaning that the participant had to come up with the correct sorting rule solely on the basis of the feedback given by the computer after each response. Only the difficult versions of the cued and the uncued task variants were used in the pre- and posttest due to their higher processing demands. In addition to the mixed-task blocks (change in sorting rule) described above, the task consisted of four single-task blocks (no change in sorting rule), one for each sorting rule. The dependent RT measures were the *switching cost* and the *mixing cost* in RTs, separately for the cued and the uncued version. The switching cost was the difference between switching and repetition-trial mean RTs, and reflects the cost of a temporary change in task-sets. The mixing cost was the difference between repetition-trial and single-task trial mean RTs, and reflects the cost of maintenance of attentional control in a context where two task sets are active. The single-task mean was derived from the single-task blocks, and the switching mean and the repetition-trial mean from the mixed-task blocks.

The Number-letter task. The task was the same as the one used in Study I, but here, two dependent measures for both RTs and error rates were employed. The first one was the switching cost that was defined as the performance difference between the switching trials and repetition trials in the mixed-tasks block. The second dependent variable was the mixing cost that was the performance difference on the repetition trials v. the single-task trials in the mixed-tasks block.

The Simon task. The task was the same as the one used in Study I, but the dependent variables were different. Here, the difference in RTs between the incongruent and congruent trials (the *Simon effect*) was used as the dependent measure. This variable reflects the extra processing cost of having to inhibit the incompatible spatial location of the stimulus. Only RTs were analyzed, due to very low error rates on this task.

The visual N-back task. The task was the same as the one used in Study I, but here the dependent variables were the processing cost (the *N-back effect*), calculated as the difference between 3-back and 1-back trials, in RTs and errors. These variables reflect the cost of managing the increased demands on WM updating.

Training paradigm

The *cued training group* practiced with the cued version and the *uncued training group* with the uncued version of the categorization task during training. During the first week the participants trained with the easier task version, and during the second week with the difficult version. The training data was not included in the statistical analyses.

Statistical analyses

ANCOVAs with posttest performance as the dependent variable and pretest performance as a covariate were run to control for group differences at pretest. The

ANCOVAs were conducted separately for the trained version (cued version for the cued training group, uncued version for the uncued training group, and an average of the cued and uncued version for the control group) and the untrained version (uncued version for the cued training group, cued version for the uncued training group, and an average of the cued and uncued version for the control group) of the categorization task. Group differences were investigated using orthogonal contrasts. The first contrast compared the two training groups to the control group and the second contrast the two training groups to each other. Furthermore, if the second contrast comparing the two training groups to each other was significant, follow-up ANCOVAs comparing the better training group to the control group were conducted. This was done to further investigate whether one of the training groups alone would outperform the controls, even though the first contrast with pooled training groups would not reach significance.

For each transfer task, similar ANCOVAs with pretest performance as a covariate, posttest performance as the dependent variable, and group as a between-subjects factor were conducted. The same orthogonal contrasts were defined for all transfer tasks as for the categorization task, and follow-up tests were run in a similar manner (see above).

4.2 Real-world training of executive functions

4.2.1 Studies IV and V

The testing session included the forced-attention DL task (Study IV), the Simon task (Study V), the Flanker task (inhibition; adapted from Eriksen & Eriksen, 1974; Study V), the visuospatial N-back task (Study V), the Number-letter task (Study V), and the Bilingual Language Switching Questionnaire (BSWQ; Rodriguez-Fornells, Krämer, Lorenzo-Seva, Festman, & Münte, 2012; Study V). In addition to this, all participants in Study IV and V were requested to fill out a questionnaire concerning their language background (e.g., age of second language [L2] acquisition, use of the different languages in everyday life in percent) and language skills (estimations of speaking, reading, writing, and speech comprehension skills on a scale from 0 [*no skills*] to 6 [*native level skills*]). Two subtests from the WAIS–III were used as estimates of overall cognitive ability: Digit span and Similarities (verbal reasoning).

The forced-attention dichotic listening task. The task materials were similar to the ones used in the pre- and posttestings in Study II, but here the participants performed only the forced-attention DL task without REA estimations. The dependent measures on this task were the number of reported syllables, separately for ear and condition.

The Flanker task. In the present version of the task, five black arrows were presented in a horizontal line at the centre of the screen. The task was to decide in which direction the arrow in the middle was pointing, irrespective of the direction of the other arrows (the flankers). On congruent trials, all arrows pointed in the same direction and on incongruent trials, the flankers pointed in a different direction than the arrow in the middle. The dependent measures on this task were the differences in RTs and error rates between incongruent and congruent trials (*Flanker effect*). These difference variables are measures of the extra processing cost caused by inhibiting the conflicting flanker arrows.

The visuospatial N-back task. The task was the same as the one used in Study I, but here, the RT and error rate differences between 2-back and 1-back trials (*N-back effect*) were used as dependent variables, and reflect the cost of managing the increased demands on WM updating.

The Bilingual language switching questionnaire. The BSWQ was used to assess individual differences in everyday language switching. The BSWQ includes 12 questions representing four subscales: (a) Tendencies to switch from Swedish to Finnish (e.g., "When I do not find a word in Swedish, I immediately tend to produce it in Finnish"), (b) Tendencies to switch from Finnish to Swedish (e.g., "When I do not find a word in Finnish, I immediately tend to produce it in Swedish"), (c) Contextual switches (e.g., "There are situations in which I always switch between languages"), and (d) Unintended switches (e.g., "It is difficult for me to control the language switches I do during a conversation (e.g., from Swedish to Finnish)". The participants responded on a 5-point scale varying from 1 (*never*) to 5 (*always*).

Three measures from the BSWQ were used in the statistical analyses: language switching, contextual switches, and unintended switches. The language switching variable was created by adding up the points on the first two subscales (Tendencies to switch from Swedish to Finnish; Tendencies to switch from Finnish to Swedish).

Statistical analyses

In **Study IV**, a mixed-model ANOVA was performed to study the effects of language and age group on the number of reported syllables in the three attention conditions per ear in the forced-attention DL task. Significant three-way interactions were studied further with univariate ANOVAs.

In **Study V**, multiple linear regression analyses were conducted on the processing cost variables (Simon effect, Flanker effect, N-back effect, mixing cost, and switching cost) of the executive tasks. Two constellations of predictors were employed. The first included three background factors: the participant's age, the age of L2 acquisition, and the percentage of the everyday use of both languages[3]. The second group of predictors included the measures from the BSWQ: language switching, contextual switches, and unintended switches. In all analyses, the predictors were inserted simultaneously.

Table 2

Overview of the Cognitive Tasks Employed at the Pre- and Posttest

				Study		
Tasks	Cognitive function	I	II	III	IV	V
Auditory letter N-back task	WM updating		X			
Letter-memory task	WM updating	X				
Visual N-back task	WM updating	X		X		
Visuospatial N-back task	WM updating	X				X
Digit span (WAIS-III)	WM	X	X[a]	X		
Letter-number sequencing (WAIS-III)	WM	X				
Auditory go/no-go spatial attention task	Inhibition		X			
Auditory-spatial interference task	Inhibition		X			
Forced-attention DL task	Inhibition		X		X	
Flanker task	Inhibition					X
Simon task	Inhibition	X		X		X
Stroop task	Inhibition		X			
Categorization task	Set shifting			X		
Number-letter task	Set shifting	X		X		X
Digit symbol (WAIS-R)	Perceptual speed	X				
Raven's Standard Progressive Matrices	Fluid intelligence			X		
Recall of concrete nouns	Episodic memory	X				

Note. [a]Only employed at the pretest

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[3] This variable was derived from the language background questionnaire. In order to obtain a measure of the everyday use of both languages, the reported percentage of the less frequently used language was subtracted from the reported percentage of the more frequently used language.

5 RESULTS

5.1 Computer-based training of executive functions

5.1.1 Study I

The results from the PET data analyses showed that there was a significant decrease in striatal D2 BP, quantified as $Z(\gamma)$, from the control condition to the updating condition, suggesting the expected increase in DA release during updating (Figure 1B). The D2 BP results also showed a significant interaction between time and group in the left caudate, stemming from the fact that there was a decrease in $Z(\gamma)$ at posttest in the training group, suggesting an increase in DA as a result of training (Figure 1C and 1D). The control group remained at baseline level.

The letter-memory behavioral data of three participants (two from the control group and one from the training group) was lost due to technical problems. The results from the ANOVA with the remaining participants showed a significant main effect of time, as the participants gave more correct responses in the posttest than in the pretest. Furthermore, a significant interaction between time and group indicated that the training group showed a greater increase in the number of correctly reported four-letter sequences over time (Figure 1A).

Regarding the transfer tasks, the results from the ANOVA on error rates in the N-back task (Figure 2) showed a tendency towards a three-way interaction between time, trial type and group. Separate follow-up three-way ANOVAs (group x time x condition) for targets and non-targets showed a significant time x group interaction for targets, indicating that the training group made significantly more correct responses than the control group on these trials. There were no significant interactions with group in the analyses on performance in the other transfer tasks.

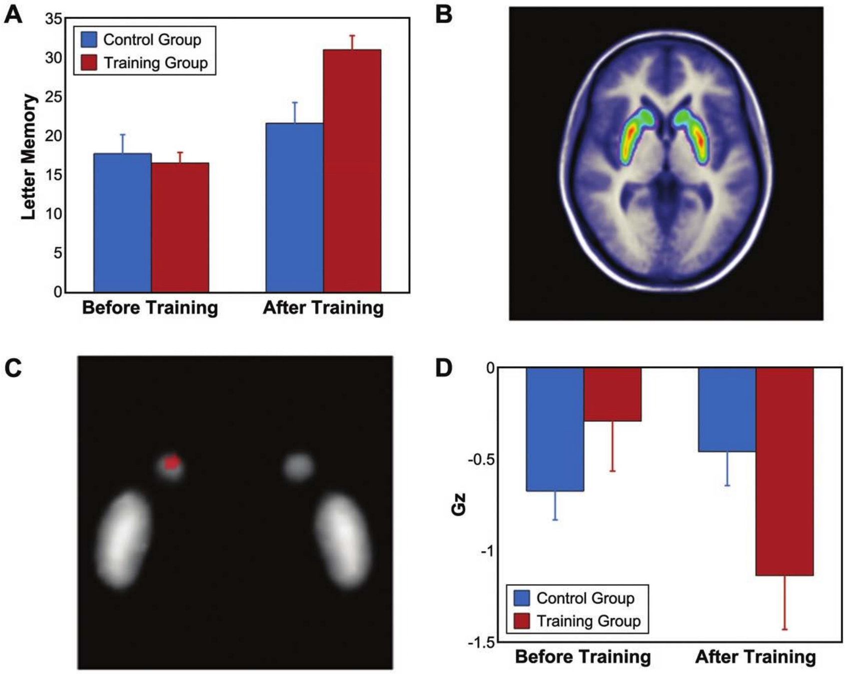

Figure 1. (A) Average number of correctly reported four-letter sequences in the WM updating condition in the Letter-memory task for the two groups before and after training in Study I. Error bars represent SEMs. (B) Lower binding of raclopride to striatal D2 receptors during WM updating compared to the control condition in the Letter-memory task before training reflects greater DA release in response to the cognitive challenge. (C) Cluster in the left caudate nucleus shows a training induced decrease of raclopride binding to D2 receptors. All voxels surviving the threshold of $p < .01$ are indicated in red on a template-striatum reference slice derived from a mean of all participant images before training. (D) Differential change in the left-caudate peak (C) for the two groups. The bars represent the difference in $Z(\gamma)$ (Gz) between the control condition and the WM updating condition in the Letter-memory task before and after training. Negative Gz values reflect lower radioligand binding during WM updating compared to the control condition. Error bars represent SEMs.

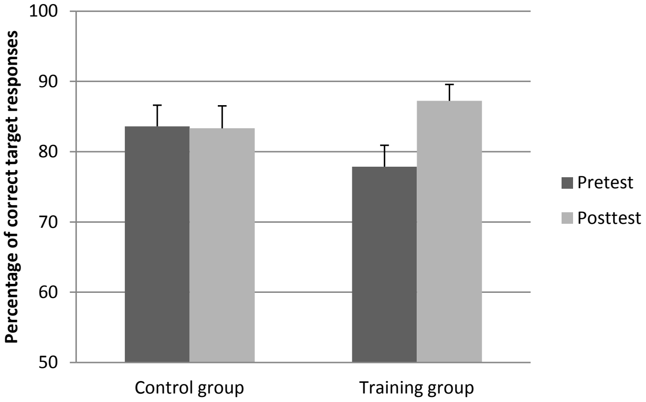

Figure 2. Average percentage of correct responses on targets (collapsed over condition) in the visual N-back task for the two groups in the pre- and postsession in Study I. Error bars represent SEMs.

5.1.2 Study II

The ANCOVA on the LI measure (Figure 3) in the NF condition showed a significant main effect of top-down training, reflecting the fact that the participants receiving top-down training showed a more leftward response pattern at the posttraining session, whereas the participants without top-down training evidenced a more rightward pattern. The main effect of bottom-up training and the interaction between bottom-up and top-down training were both non-significant. The results from the ANCOVA on overall performance in the NF condition (Figure 4) showed no significant main effects or interactions.

The LI analyses in the FL condition showed no significant effects, but the analysis on overall performance revealed an almost significant main effect of top-down training, reflecting the fact that the participants receiving top-down training reported more syllables overall in the FL condition at the posttest session than the participants without top-down training. All other effects were non-significant. The analyses on LI and overall performance in the FR condition showed no significant effects.

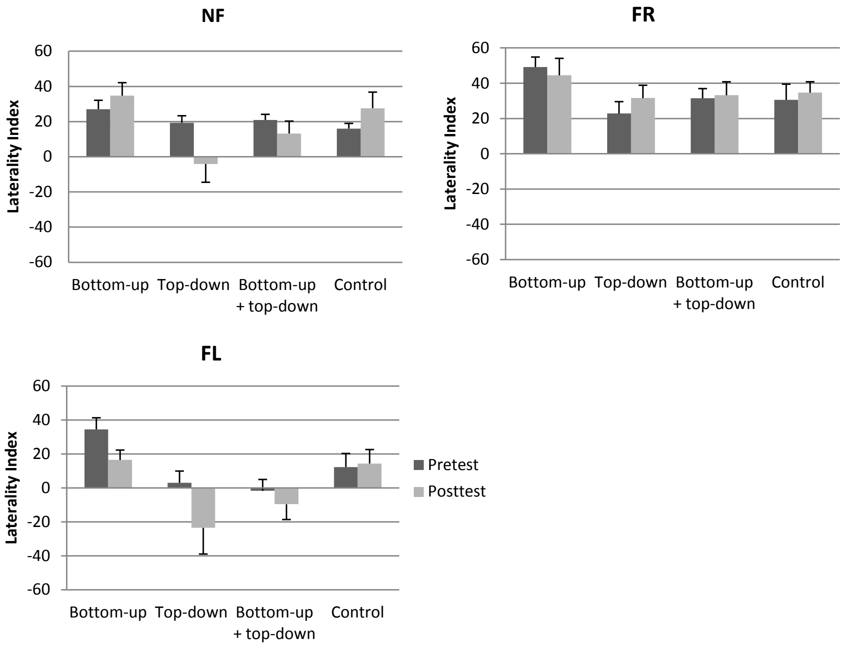

Figure 3. Laterality indices in the non-forced (NF), forced-right (FR), and forced-left (FL) dichotic listening conditions for the four groups in the pretraining and posttraining assessments in Study II. Error bars represent SEMs. Positive values indicate a rightward response pattern and negative values a leftward response pattern.

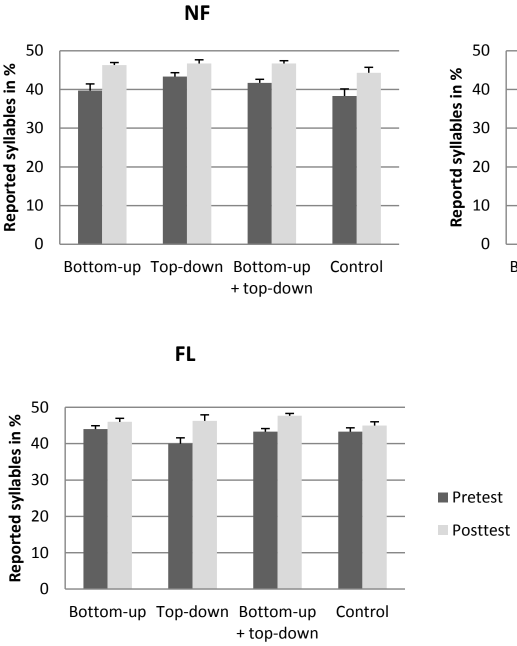

Figure 4. Average percentage of reported syllables irrespective of the ear in the non-forced (NF), forced-right (FR), and forced-left (FL) dichotic listening conditions for the four groups in the pretraining and posttraining assessments in Study II. Error bars represent SEMs.

Regarding the transfer tasks, the analyses of incorrect key presses in response to dichotic targets (i.e., when participants erroneously responded only to either the left- or the right-ear target although the task was to press both response keys) in the slower version of the auditory go/no-go spatial attention task (Figure 5), showed a significant three-way interaction between time, response key, and top-down training. Subsequent two-way ANOVAs (time x top-down training) run separately for the left- and right-key responses showed a tendency to an interaction between time and top-down training for left-key responses, stemming from an increase in left-ear reports for participants with top-down training and a decrease in left-ear reports for the others. The ANOVA on right-key responses revealed a significant interaction between time and top-down training, due to the fact that right-key responses increased among participants not receiving top-down training and decreased in participants who received top-down training.

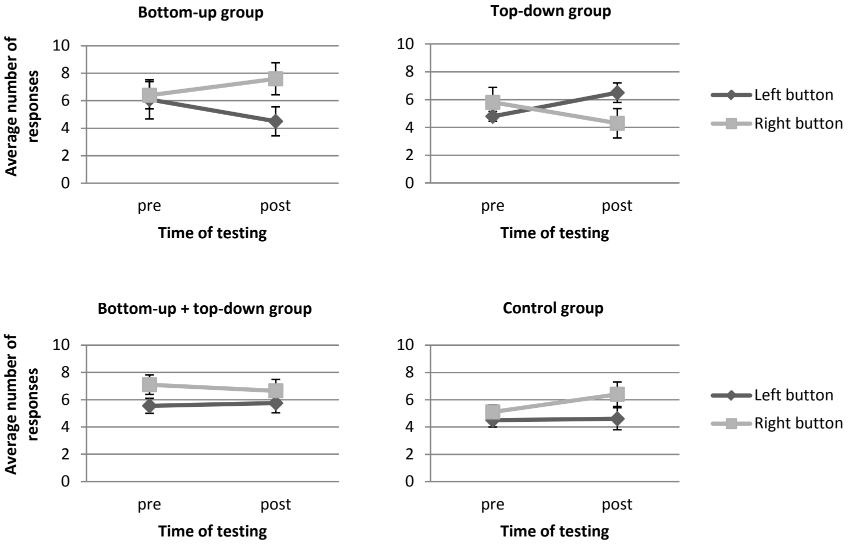

Figure 5. Average number of only right- or left-key presses in the simultaneous bilateral (dichotic) target presentation in the slower version of the auditory go/no-go spatial attention task for the four groups in the pretraining and posttraining assessments in Study II. Error bars represent SEMs.

5.1.3 Study III

The results from the ANCOVAs on the trained task showed a significant main effect of group for the switching cost. The planned contrasts revealed a trend towards a smaller switching cost in the training groups than in the control group at posttest. The second contrast showed that the switching cost was significantly smaller at posttest in the cued group than in the uncued group. A follow-up ANCOVA comparing the cued group to the control group showed that the switching cost was significantly smaller in the cued group at posttest. The ANCOVA on the mixing cost showed no significant effects.

The results from the ANCOVAs on the untrained task showed a significant main effect of group for the switching cost. The planned contrasts revealed no significant difference between the training groups and the control group, but showed that the uncued group had a significantly smaller switching cost at posttest than the cued group. A follow-up ANCOVA comparing the uncued group to the control group showed that the posttest switching cost was significantly smaller in the uncued group.

The analysis on the mixing cost in the untrained task also revealed a significant main effect of group. The planned contrasts showed a tendency towards a smaller switching cost for the training groups compared to the control group. The second contrast showed that the mixing cost was significantly smaller for the uncued group than for the cued group. A subsequent ANCOVA comparing the uncued group to the control group showed that the mixing cost at posttest was significantly smaller in the uncued group. Important to note here is, however, that the average mixing cost in fact increased from pretest to posttest in all groups on the untrained task variant.

Regarding the transfer tasks, the ANCOVA on error rates in the N-back task showed a significant main effect of group, stemming from significantly higher error rates in the training groups than in the control group at posttest. The second contrast comparing the training groups with each other was not significant. The results from the analyses on performance on the other transfer tasks revealed no significant differences between groups.

5.2 Real-world training of executive functions

5.2.1 Study IV

The results from the analyses on performance in the forced-attention DL task showed a significant main effect of attention condition, with the participants having the highest number of correct responses in the FR condition, and the lowest in the FL condition. The results also showed a significant main effect of ear, indicating the expected right-ear dominance across attention conditions. The performance was not significantly affected by age, but there was a significant main effect of language background, indicating that bilinguals in general had a higher number of correct responses than monolinguals. The results also showed a significant interaction between attention condition and ear, stemming from the fact that the participants, as expected, modulated their attention according to task instructions. Furthermore, there was a significant three-way interaction between attention condition, ear, and language group. Follow-up univariate ANOVAs for both ears separately within each attention condition and using pooled age groups, showed that the bilinguals excelled the monolinguals in directing attention to the target ear and inhibiting the irrelevant information in the non-target ear in the forced-attention conditions (Figure 6). The results also showed a significant main effect of language group, indicating that the bilinguals reported more syllables in all conditions overall, irrespective of ear (Figure 7).

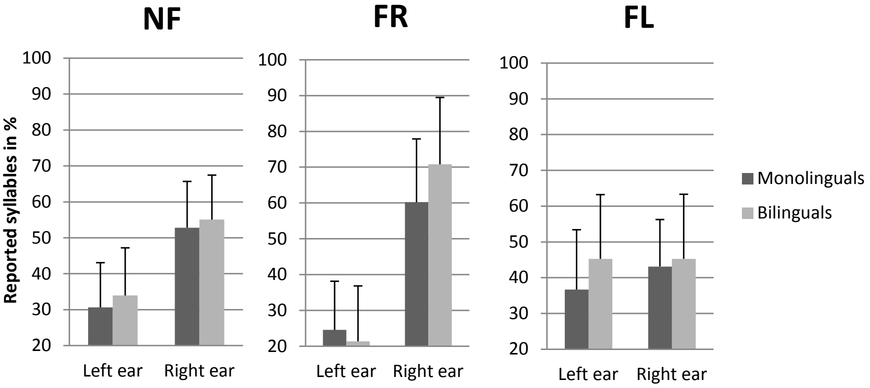

Figure 6. Average percentage of correctly reported syllables (SD) per ear in bilinguals and monolinguals (collapsed over the age groups) in the non-forced (NF), forced-right (FR), and forced-left (FL) dichotic listening conditions in Study IV.

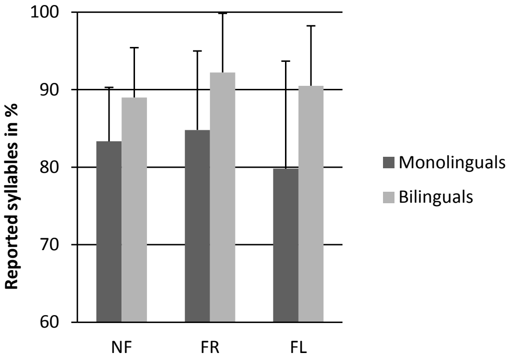

Figure 7. Sum of correct responses (SD) in percent for left and right ear, for monolinguals and bilinguals in the non-forced (NF), forced-right (FR), and forced-left (FL) dichotic listening conditions (collapsed over the age groups) in Study IV.

5.2.2 Study V

Regarding RTs, the multiple regression model with the predictors age, age of L2 acquisition, and everyday use of both languages was significant for the Simon effect, and the mixing cost in the Number-letter task. The results also showed a significant association between age of L2 acquisition and the Simon effect, indicating that younger age of L2 acquisition resulted in a smaller Simon effect in RTs. Furthermore, all three predictors were marginally significant in predicting the mixing cost, so that younger age, earlier L2 acquisition, and a more balanced use of both languages in everyday life was associated with a smaller mixing cost. The multiple regression model with the three BSWQ predictors was significant for the mixing cost in the Number-letter task, but none of the individual predictors reached significance in this analysis.

With regard to errors, the multiple regression model with age, age of L2 acquisition, and everyday use of both languages was significant for the N-back effect. There was a significant association between the predictor age and the N-back effect as an outcome variable so that younger age resulted in a smaller N-back effect in errors. The results also showed that the multiple regression model with the three BSWQ predictors was significant for the mixing cost. Language switching was a significant predictor in this analysis: the more a participant tended to switch from Swedish to Finnish and vice versa, the smaller the mixing cost in errors in the Number-letter task was.

6 DISCUSSION

6.1 Computer-based training of executive functions

The aim of studies I-III was to investigate the trainability of the three EF suggested by Miyake et al. (2000): WM updating, inhibition, and set shifting, and to study to what extent training of these functions can transfer to other untrained tasks. The results can be divided into effects on the trained task, effects on tasks measuring the same EF (near transfer), and effects on tasks measuring other EF (far transfer). From the clinical perspective, the ultimate goal of cognitive training studies is to cause general improvement, i.e., far transfer, but also near transfer indicates some degree of generalizability of training. Improvement on the trained task is expected and self-evident. However, it also provides a measure of participants' engagement in training. Study I also included a functional neuroimaging component, the aim of which was to find out if WM updating training affects DA release in the striatum.

6.1.1 Improved performance on the trained task

As expected, in all studies, training improved performance on the trained task from pretest to posttest. In **Study I**, the behavioral results showed that the training group improved more than the control group on the Letter-memory updating task, used both in training and in the pre- and postsessions. In **Study II**, the results showed that top-down training, irrespective of whether it was applied alone or in combination with bottom-up training, led to an increase in the number of reported syllables in the FL condition, whereas bottom-up training did not yield any significant effects. Interestingly, the participants with top-down training also showed a more leftward response pattern in the NF condition, while the participants without top-down training had a more rightward pattern. No effects of training were seen in the FR condition. In **Study III**, the results showed that set shifting performance improved particularly on the cued variant of the categorization task, regardless of the form of training the groups had received. This is most likely attributed to the fact that the cued categorization task was easy enough to reveal improvement after two weeks of training. We expected that uncued training would result in a better training outcome than cued training, due to higher processing requirements of endogenously generated shifts in set (Barceló, Muñoz-Céspedes, Pozo, & Rubia, 2000). The results, however, did not support this idea, as performance improved only on the cued task version.

6.1.2 Near transfer as a result of training

In **Study I**, the results showed that the training group improved also on an untrained task (n-back task) measuring WM updating, indicating near transfer of WM updating training. The results are similar to the study by Dahlin et al. (2008), using the same training paradigm and the same transfer task.

The results from **Study II** showed that top-down training with the forced-attention DL task resulted in near transfer to the auditory-spatial domain. The near transfer effect was seen in the error patterns on dichotic targets in the auditory go/no-go spatial attention task. In this situation, two targets were presented at the same time to both ears and participants were to press both response keys. Before training, failures to recognize the dual stimuli more often resulted in right-key responses than left-key responses for all participants, mirroring the REA in the DL task. However, there was a significant decrease in right-key responses and a tendency toward an increase in left-key responses as a result of top-down training, whereas participants who did not receive top-down training showed the opposite trend. Taken together, the results from the NF condition and the near transfer effect to the auditory go/no-go spatial attention task suggest that top-down training with a focus on the left auditory space increases leftward allocation of attention even when such an allocation is not explicitly called for by the task. This finding stands in contrast with the results from participants without top-down training, who at the post-training assessment showed a more rightward response pattern in both the NF condition and in the transfer task. However, the fact that the rightward pattern was present not only in the bottom-up group but also in the control group suggests that it is related to other factors than bottom-up training (e.g., being exposed to multiple testing).

The results from **Study III**, showed no effects of near transfer as a result of either cued or uncued set shifting training. These findings are not in line with previous set shifting training studies showing near transfer (Karbach & Kray, 2009; Minear & Shah, 2008). A possible reason for this may be that the near transfer tasks in the previous set shifting training studies have had close resemblance to the training tasks used, while the training tasks and the near transfer task in the present study were quite different from each other.

6.1.3 Far transfer as a result of training

The studies in the present thesis show no far transfer effects as a result of training. This contradicts some studies (e.g., Brehmer et al., 2012; Karbach & Kray, 2009; Minear & Shah, 2008; Mozolic et al., 2011; Rueda et al., 2005; Salminen, Strobach, & Schubert, 2012), but supports the idea that training gains are quite process-specific, and that transfer is possible only when the training task and the transfer task engage the same cognitive processes and overlapping neural systems (Dahlin et al., 2008; Klingberg et al., 2005). The results are also in line with the recent view (Green & Bavelier, 2008; Melby-Lervåg & Hulme, 2012; Morrison & Chein, 2011; Shipstead et al., 2010) that general improvement (far transfer) is difficult to achieve as a result of executive training.

6.1.4 The effects of working memory training on striatal dopamine release

The results from **Study I** showed enhanced DA release after WM updating training. This is in line with the occupancy model (for a review, see Laruelle, 2000), suggesting displacement of radioligand to D2 receptors during cognitive processing. More importantly, the results indicate that there is a link between the previously observed increases in striatal blood-flow (Dahlin et al., 2008) and DA release as a result of WM updating training. Although previous research has established the link between WM and DA (for e review, see Cropley et al., 2006), the results from Study I provide direct evidence for the role of DA in training of WM updating. Furthermore, these findings highlight the important role of the association between transient neural processes and striatal D2 receptor activity in human WM functioning.

6.2 Real-world training of executive functions

The aim of Study IV was to investigate whether bilingualism would facilitate inhibition in an executive phonological task, namely the forced-attention DL task (Hugdahl et al., 2009). The aim of Study V was to investigate the bilingual advantage in EF further by exploring possible relationships between bilinguals' everyday language use and the level of their executive skills.

6.2.1 Inhibition skills in bilinguals v. monolinguals

Monolinguals and bilinguals from two age groups participated in **Study IV**. As regards standard, NF DL, all groups demonstrated a significant REA. Furthermore, the results showed that the bilinguals reported significantly more targets from the right ear in the FR condition and from the left ear in the FL condition than the monolinguals. This is in line with the bilingual advantage hypothesis, as previous research has suggested that managing the FL and FR attention conditions requires inhibition of the stimuli presented in the opposite ear and directing attention to the attended ear (Hugdahl et al., 2009). The results from this study, thus, suggest that the bilinguals are more effective in inhibiting task-irrelevant information, which supports previous research using visual tasks (for a review see Bialystok, 2009; Bialystok et al., 2012) and indicates that lifelong bilingualism can serve as a kind of real-world training of EF.

In contrast to some previous findings (Andersson et al., 2008; Hugdahl, Carlsson, & Eichele, 2001; Takio et al., 2009; Thomsen, Specht, et al., 2004) , however, we failed to find an age effect on the ability to modify the REA. While neither the younger nor the older participants were able to convert the REA to a LEA in the FL condition, both groups exerted top-down control to the extent that the difference between ears became minimal. Thus, even our older group could modulate their attention to a significant degree, which was not the case in the studies of Takio et al. (2009) and Thomsen, Specht et al. (2004). However, in the studies by Andersson et al. (2008) and Hugdahl et al. (2001), the older age group was able to modulate their attention in the FL condition. One possible explanation for the good performance in older adults in both the Andersson et al. (2008) study and the present study may be the fairly high level of education in both of these studies (on the average 14.0 and 14.6 years, respectively), which tends to correlate positively with overall intellectual capacity as measured by cognitive tests. Education or SES was not reported by Hugdahl et al. (2001), Takio et al. (2009) or Thomsen, Specht et al. (2004).

Furthermore, the results from Study IV showed that the bilinguals had more correct responses overall. A possible explanation for this may lie in differences in perceiving voiced (/b d g/) and unvoiced (/p t k/) consonants by Finnish monolinguals v. Finnish–Swedish bilinguals. In Finnish, the voiced consonants /b/ and /g/ exist only in loan words, and are often pronounced as /p/ and /k/ (Karlsson, 1983). In contrast, the same consonants are frequently used in the Swedish language. Consequently, it is possible that the Finnish–Swedish bilinguals are better in distinguishing between the voiced and unvoiced consonants in a DL situation. However, since this ability depends on a fine-grained analysis of sound duration that can be attributed to left hemisphere function (Brancucci, D'Anselmo, Martello, & Tommasi, 2008), a small difference in discriminability of the stimuli between monolinguals and bilinguals may play a role in the FR condition, but not in the FL condition. The results from the present study support this idea, since the group difference was larger in the FR condition. Nevertheless, the results also showed a significant difference in target ear reports in favor of the bilingual group in the particularly demanding FL condition, suggesting an executive advantage in bilinguals.

6.2.2 Bilingual language use and executive skills

Although the possible bilingual advantage in EF has been assessed in several studies, the research field has solely relied on the natural group design where bilinguals are compared to monolinguals. As a consequence, it is hard to rule out possible confounding factors that may covary with the variable of interest, i.e., language background. **Study V** was an attempt to introduce a complementary analysis approach to study the bilingual advantage in EF and its underlying mechanisms. In a sample of Finnish–Swedish early bilinguals, we found that the more a bilingual switched between languages in everyday life, the smaller the mixing cost (i.e., better mixing ability) in errors was in the set shifting task. In broad terms, this result provides support for the assumption that the bilingual advantage in EF stems from a lifelong experience in managing two languages that calls for executive resources (Abutalebi & Green, 2007; Bialystok et al., 2009; Green, 1998; Meuter & Allport, 1999; Moreno et al., 2008; Rodriguez-Fornells et al., 2006; Ye & Zhou, 2009)

In the present study, it was the mixing cost and not the switching cost in the set shifting task that showed sensitivity to the bilingual experience. It has been suggested that the switching cost and the mixing cost engage different cognitive control processes. The switching cost has been defined as a measure of task-set reconfiguration (Rogers & Monsell, 1995), interference from the previous task-set (Allport, Styles, & Hsieh, 1994), or a combination of both (Monsell, 2003; for a review, see Kiesel et al., 2010). The underlying cognitive mechanisms of the mixing cost have been under debate. Rogers and Monsell (1995) proposed that the performance difference between single-task blocks and mixed-task blocks is due to an increased WM load, as two different task sets need to be maintained in the mixed-task blocks. However, Rubin and Meiran, (2005) showed that the mixing cost is related to a top-down management of competing task sets, and not to WM load. The mixing cost may, thus, set more demands on sustained control processes, reflecting the constant need to keep different task-sets active or to maintain attentional monitoring processes, in order to efficiently react to changes in the task. The switching cost, on the other hand, may be related to transient control mechanisms, such as reconfiguration of goals or the linking of task cues to their appropriate stimulus–response mappings (Braver, Reynolds, & Donaldson, 2003). In other words, the effect of bilingual language switching on the mixing cost seen in Study V, could be explained by the idea that a task-decision process taking place in the mixed-tasks block resembles the bilingual situation where a decision of which language to use has to be made in each conversation.

The results from Study V may thus give some clues as to which aspects of bilingual language use are important for the executive gains: it might be that language selection and keeping both languages active are more important for the bilingual advantage than inhibition of the non-target language, as has also been suggested in recent literature (Hilchey & Klein, 2011). This is in line also with the scanty associations between the predictors and the inhibition tasks, although one should note that the Flanker task and the Simon task may not have been demanding enough for stronger relationships to appear. Contrary to the present findings, however, Prior and MacWhinney (2010) found a bilingual advantage in the switching cost, but not the mixing cost, in a study with young adults (see also Garbin et al., 2010).

One should also note that the present results showed an effect of language switching, but not contextual switches, on the mixing cost in the set shifting task. One possible reason for this may be that the questions in the language switching subscale concern language switching in general (i.e., whether the bilingual typically tends to use a word from the non-target language when the correct word in the target language cannot be retrieved quickly enough). It may be that this type of language switching is related to more sustained control processes, similar to the ones that have been suggested to be involved in the mixing cost. The contextual switches, on the other hand, may be more situation-bound, as the subscale includes questions as to whether there are specific situations and topics where the bilingual tends to mix both languages. This subscale does not give information about the frequency of occurrence for these situations in everyday life. Costa, Hernández, Costa-Faidella, and Sebastián-Gallés (2009) speculates that those bilinguals who mostly use the two languages in different contexts and do not frequently switch between them, may not show an advantage in monitoring processes, as they end up having less practice on language monitoring. The frequency of unintended switches did not predict executive performance either, probably because they reflect temporary processes that cause fluctuations in attentional control. Based on this discussion, the results from Study IV can also be interpreted in a different way. The bilingual advantage on the forced-attention DL task may be a result of more effective monitoring skills, i.e., selecting the relevant information and suppressing the irrelevant information, and not from better inhibition skills per se.

6.3 Implications of the results and future directions

Human beings have an exceptional capacity to learn and adapt to new environments. However, despite the large number of previous training studies, there is still little consensus about whether more general cognitive improvement can be achieved as a result of systematic training of specific cognitive functions, and if so, how this improvement could be achieved. The results from the computer-based training studies in the present thesis (unfortunately enough) support the recent claims regarding the effects of executive training; improvement beyond the trained task and closely related tasks seems to be more of an exception than a rule. Still, these findings do not necessarily lead to the conclusion that more general cognitive improvement through computer-based training of EF is impossible, but simply that this is less likely with the present training regimes. However, although the present studies failed to find clear general improvement, Study I indicates that computer-based training of WM updating can cause alterations at the neural level.

Nevertheless, the results from Study IV suggest that lifelong real-world training in the form of bilingualism is related to EF advantages. Study V supports this idea by suggesting that the more training a bilingual gets in language switching in everyday life, and the earlier in life the training has begun, the better the executive performance gets. These findings are in line with previous studies showing that general improvement is more likely after training that corresponds to real-life experiences, such as action video game training, musical training, or athletic training, than after computer-based short-term training in the laboratory (Green & Bavelier, 2008). Thus, it is possible that real-world training may provide an answer as to which elements of the training paradigm are important for achieving more general improvement.

The most obvious difference between the real-world training and the laboratory training studied here lies in the duration and the amount of training. This difference is probably the main reason for the fact that more general improvement was seen in bilinguals than after laboratory training. However, conducting studies with longer periods of laboratory training is often not feasible (however, see Schmiedek, Lövdén, & Lindenberger, 2010 for 100 days of EF training). Another essential difference between real-world training and computer-based training is that the natural training involves a wider spectrum of cognitive abilities at the same time. In laboratory training research, on the other hand, the aim is to separate these cognitive abilities into specific functions, such as inhibition, set shifting, or WM updating (Green & Bavelier, 2008), so that the process causing the possible improvement can be identified (Morrison & Chein, 2011). Many training paradigms are in fact based on the idea that training a cognitive process will cause improvement of that process, almost like strengthening a muscle by exercising it (Melby-Lervåg & Hulme, 2012). Green and Bavelier (2008) discuss other possible differences between computer-based and real-world training, and highlight a few major points. In real-world training, the level of difficulty usually increases as the skills improve, and when the level of difficulty is slightly higher than the individual's current ability, the motivation is high and learning is effective. Learning is also more effective when the tasks are varying, so that the individuals have to create more general principles about the information being learned and the context they appear in. Finally, feedback or rewards may help learning.

Some of these features have been included in the computer-based training regimes in the present thesis. For example, the training paradigm in Study I included several tasks with different stimuli, in order to make the WM updating training more general. In all computer-based training studies, the level of difficulty was increased when the skills improved. Furthermore, the participants in Study I received feedback after each day of training. It is thus possible that the positive outcome from the WM updating training in Study I would partly be due to these aspects.

To what extent the bilingual advantage in EF can be interpreted as actual transfer of training is, however, perhaps not that simple to determine. One could argue that the processes underlying the skills that are being “trained” in bilinguals and the skills that are required in the different computer-based executive tasks used in the laboratory are to some degree the same. In line with this, the bilingual advantage would be considered near transfer. However, irrespective of whether the bilingual “training” stems from inhibition of the language not in use (e.g., Abutalebi & Green, 2007) or from monitoring the activation of the two languages (e.g., Hilchey & Klein, 2011), these cognitive processes seem to be quite different from the processes involved for example in inhibiting the irrelevant spatial information of the colored square in the Simon task or in shifting between letter and number categorization in the Number-letter task (see also Green & Bavelier, 2008, regarding effects of playing action video games). One could thus argue that the transfer effect in bilinguals would actually be of a more general nature (see also Stocco et al., 2012).

Determining the distance of transfer is not uncomplicated, as it requires information about the degree of similarity between different tasks (see e.g., Noack, Lövdén, Schmiedek, & Lindenberger, 2009). In this thesis, the classification into near and far transfer has been made based on the cognitive function the transfer task is assumed to tap. If for example performance improves on a task that is assumed to measure the trained function, the distance of transfer is considered near. Improvement on a task thought to measure an untrained function, on the other hand, is considered far transfer. However, tasks that are assumed to measure the same cognitive ability may in fact engage quite different processes, whereas tasks that are thought to tap different cognitive functions may nevertheless share underlying processes.

The reason for not achieving general improvement as a result of executive training in previous research and in the three studies investigating computer-based training in the present thesis may also be partly due to methodological issues. As previously mentioned, WM training studies have recently received criticism for not applying adequate methodological criteria (Melby-Lervåg & Hulme, 2012; Morrison & Chein, 2011; Shipstead et al., 2010). These points of criticism include the lack of a contact control group, of not randomly assigning participants to groups, and of using only one task to measure an entire cognitive ability. The fact that we employed a no-contact control group in Study I, may, thus, have affected the results through for example differences in effort, expectancy, and investment (Morrison & Chein, 2011). The results from the present study were, however, consistent with the results from a previous study (Dahlin et al., 2008), using the same training paradigm and transfer task. However, Dahlin et al. (2008) employed a no-contact control group as well, and results from studies with an untreated control group are typically difficult to replicate using a treated control group (Melby-Lervåg & Hulme, 2012). A no-contact control group was also employed in Study III, but the results showed no transfer effects to other tasks.

In the studies investigating computer-based training, the participants were randomly assigned to the different groups. However, in Study III, the participants were first matched based on their pretest performance on one executive measure, and after that randomized into the three groups, in order to avoid possible confounds due to differences in pretest performance.

Further, the transfer tasks used in Studies I-III in several cases included only one task to measure a cognitive function. Thus, even though the results from studies I-II show near transfer to an untrained task, it is important to note that the transfer effect was visible only in one of the transfer tasks. In study I, the training transferred only to the n-back task with digits, and not to the visuospatial version of the same paradigm. Moreover, training with the forced-attention DL task in Study II showed transfer to one condition in the auditory-spatial attention task, but not to other measures of inhibition. More specifically, the observed near transfer effect in Study II seems to be limited to situations where two equivalent auditory signals compete for attention in space, as there was no transfer to the auditory-spatial interference task with monaural stimulus presentation. Related to this, one basic obstacle when investigating the effects of training of EF (regardless of whether it is real-world or laboratory-based training), is the validity of the tasks employed (e.g., Barkley, 2012). This has received surprisingly little research interest, despite the fact that executive tasks are frequently used both in research and in clinical contexts. One reason for this may be that the concept of EF itself has not yet been clearly defined. The problem with the uncertainty regarding what functions the commonly used tasks measure, was addressed in the previously mentioned study by Miyake et al., (2000; see the Introduction). The model with the best fit indicated the existence of three latent EF (WM updating, inhibition, and set shifting). Of the tasks employed in the present thesis, the Number-letter task was used as a measure of set shifting (showing a standardized factor loading of .57 on this latent function), the Letter-memory task as a measure of WM updating (with a factor loading of .63), and the Stroop task as a measure of inhibition (with a factor loading of .40) in the model by Miyake et al. (2000). Furthermore, regarding the WCST, the results from the Miyake et al. (2000) study indicated that of the three latent functions studied, only the effect of set shifting was significant. However, this analysis only included some executive tasks, and the relevance of many executive tasks is based on face validity.

Important to note here is also that the use of the three executive functions identified by Miyake et al. (2000) as a theoretical basis for the present thesis could be questioned. The emergence of these three factors in the Miyake et al. (2000) study is dependent on the tasks employed. In other words, using different tasks could result in another set of components of executive functions. The factor analysis can simply reflect the diversity of the tasks used and not the diversity of executive functions, particularly when the validity of the tasks is low (Barkley, 2012).

In addition to the methodological criticism pointed out in the recent reviews mentioned above, a common problem in training studies is the small number of participants, which decreases the statistical power and increases the risk for Type II errors. The group sizes in Studies I-III varied from 10 to 20. The lack of larger differences in training outcomes between the training and the control groups in all studies, may, thus, partially be due to quite small group sizes, which makes identification of small intergroup differences difficult. Sensitivity power analyses (with an α-level of .05 and power of .8) indicate that only large effects, $\eta^2_{\text{partial}} = .135$ - $.198$ (Cohen's $f = .395$ - $.498$; small, medium, and large as defined by Cohen, 1988), can be detected with the sample sizes used in Study I-III. The effect sizes for the non-significant interactions with group and time in the near transfer task (Number-letter task) in Study III, for example, range from $\eta^2_{\text{partial}} = .015$ to $\eta^2_{\text{partial}} = .075$, (with the best performance in the uncued group) indicating small to medium effects, not large enough to be detected by the statistical test. The reason for having small groups in this type of studies is mainly related to the fact that the training period is very time-consuming. In study II, for example, 50 participants train four times (à 30 minutes) per week for four weeks. Also, in Study I, the use of PET limits the size of the groups.

The reason for not finding more general transfer after executive training may also be that we used healthy adults as participants in all studies. In fact, many previous studies have shown that WM training in clinical samples can be effective and result in both near and far transfer (for a review, see e.g., Klingberg, 2010). Furthermore, the participants in the training studies in the present thesis were young university students. It is possible that children and older adults would show greater training gains, as many EF have been shown to be at their peak in young adults (Kramer, Hahn, & Gopher, 1999; Kray, Eber, & Lindenberger, 2004). The age effect on EF may be exacerbated in university students who are likely to be particularly efficient in these functions and therefore have limited possibilities for further executive improvement. However, previous studies suggest that far transfer is actually more common in young adults than in old adults (Brehmer et al., 2012; Schmiedek et al., 2010), and a recent WM training study (Salminen et al., 2012) reported both near and far transfer in university students. It is therefore plausible to think that the reason for differences in training results between studies lies somewhere else.

Finally, the type of training tasks used in the present group of studies could conceivably have affected the outcomes. For example, the WM updating training tasks used in Study I may have led to the use of chunking (i.e., grouping of items for easier recall) as a strategy in order to perform better on the task. In this case, the training would have been more of a training of strategy, instead of training of WM updating per se (Morrison & Chein, 2011). Even though chunking requires updating to some degree (throwing away the irrelevant chunk and replacing it with a new chunk) the amount of updating training would not be the same compared to item-by-item updating. Based on self-reports collected after each week of training, only three participants in the training group seem to have been using chunking as the strategy to solve the task. Furthermore, in Study III, the structure of the training task may have affected the results. The categorization task has relatively long repetition-trial sequences, which means that the participants get much practice also on the repetition trials. As the repetition trials and single-task trials in the categorization task are quite similar (due to the fact that the repetition trials in most cases represent the later trials in a set when the new set has already been established) the performance on the repetition trials and the single-task trials may improve to the same extent, and the mixing cost remains the same. This could explain the lack of training-related changes in the mixing cost in the categorization task.

In order to improve training paradigms, the next step would be to study the underlying mechanisms of the training and transfer tasks used in training research. This would offer answers to the question of why some studies find transfer as a result of training, while others do not. For example, by manipulating certain aspects of the training and the transfer tasks, such as inhibitory or set shifting demands in WM updating tasks (e.g., one group training WM updating with low demands on inhibition and another group training WM updating with high demands on inhibition, or including WM updating transfer tasks with different demands on inhibition), one would be able to more specifically determine which underlying mechanisms in training lead to transfer.

Further, the results from Study I provide information about the underlying neural mechanisms of WM updating training, and suggest that improved WM updating performance enhances DA release in the striatum. Future studies should investigate if the same phenomenon occurs during transfer task performance after training. It would also be interesting to see if the bilingual advantage is related to enhanced DA release. The Conditional Routing Model proposed by Stocco et al. (2012) suggests that the source of the bilingual advantage in EF is that bilingualism trains the gating system in the striatum for information going to the prefrontal cortex. An alternative (or complementary) explanation comes from a recent study investigating cortical thickness and hippocampal volumes in interpreters before and after a ten-month period of intense language studies (Mårtensson et al., 2012). In addition to increases in cortical thickness in language-related brain areas (the left middle frontal gyrus, inferior frontal gyrus, and superior temporal gyrus) in the interpreters compared to the controls, the results also showed that hippocampal volumes increased significantly more in the interpreters as a result of their intensive cognitive training. The authors speculated that this structural change in the hippocampus may constitute a mechanism behind the findings shown by some studies (Bialystok, Craik, & Freedman, 2007; Craik, Bialystok, & Freedman, 2010) that bilingualism can delay the onset of symptoms of dementia.

Regarding real-world training, previous studies showing enhanced EF in bilinguals have exclusively employed a natural group design (bilinguals contrasted to monolinguals) and have thus been unable to rule out all possible confounding factors that could contribute to the observed group differences (e.g., Morton & Harper, 2007). This is a potential problem also in Study IV, although we controlled for many possible confounds, such as SES, which is a common criticism against this type of studies. However, while the results from Study V are preliminary, the multiple regression approach used, focuses on the bilinguals and is thus not to the same degree hampered by the unavoidable methodological problems of natural group designs. Nevertheless, also the present approach shares the shortcomings of designs that do not enable the randomization of participants. It is possible that some background factors may affect the way in which the bilinguals use their two languages in everyday life, and these factors could bear relevance to their executive abilities. It is also important to keep in mind that regression analyses represent a correlational approach and thus cannot prove causality. However, being a bilingual is not something an individual chooses to be, and therefore not dependent on interest or talent. Instead, bilingualism is something the individual is required to be, due to the circumstances the individual lives in (Bialystok et al., 2012). It therefore seems unlikely that bilingual behavior, such as switching between languages, would be related to individual differences in qualification. There is, however, no doubt that both the measurement of the various aspects of bilingual experience and the mechanisms behind the bilingual advantage need to be clarified further in future studies. Ultimately, longitudinal data is needed to establish causal connections between bilingualism and enhanced cognition. Finally, it is, also important to note that although bilingualism seems to improve some EF, and even postpone symptoms of dementia, the differences are small and probably not detectable in everyday life.

SUMMARY AND CONCLUSIONS

The present thesis investigated the trainability of three EF through computer-based training in the laboratory and real-world training in the form of bilingualism. The key findings and conclusions of the thesis are as follows:

1. WM updating training enhanced DA release in the striatum (Study I).

2. WM updating training elicited near transfer, but not far transfer (Study I).

3. Training inhibition resulted in near transfer, but not in far transfer (Study II).

4. Top-down training of inhibition resulted in near transfer, while bottom-up training did not generalize to other untrained tasks. This indicates that inhibition in the auditory modality in adults can be modulated by training that engages high-level executive processes (Study II).

5. Set shifting training improved performance only on the easier training task version, but did not result in near or far transfer (Study III).

6. Training with unpredictable set shifting was not more effective than training with predictable set shifting (Study III).

7. Bilinguals are better on inhibition, as measured by the forced-attention DL task. However, an alternative explanation based on recent research and Study V in the present thesis, is that bilinguals are better in monitoring competing information, i.e., in selecting the relevant information and inhibiting the irrelevant information (Study IV).

8. Language switching predicted the mixing cost performance in the set shifting task, so that more frequent language switching was associated with a smaller mixing cost in errors (Study V).

9. Younger age of second language acquisition was associated with a smaller cost of inhibition (Simon effect) in RTs (Study V).

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