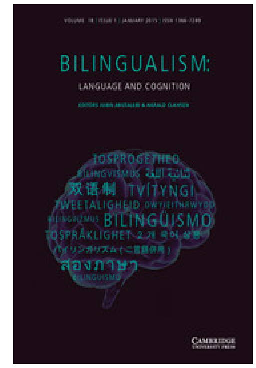

Bilingualism and cognition

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KEYNOTE ARTICLE

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The relation between bilingualism and cognition is informative about the connection between language and mind. From the perspective of language, the question is how bilingualism might help or hinder cognition – narrowly interpreted here as executive function. From the perspective of higher cognition, the question is what kinds of experiences improve executive function. Reported cognitive benefits from bilingualism range from none to substantial as a function of age, type of bilingualism (e.g., life-long balanced vs later-onset or infrequent use of the other language), syntactic relation between the two languages, socio-economic and immigrant status, task, and laboratory. To understand the variability and inconsistencies in results with bilingualism, I analyze concepts of executive function and cognitive reserve and examine the range of factors (such as active video game playing, education, musical training, and aerobic exercise) that are known to correlate with or to improve executive function. I suggest that a) "executive function" is a complex set of cognitive processes, the components of which are sometimes minimally correlated with each other, depending on the task; b) bilingualism is inconsistently correlated with superior executive function and delayed onset of dementia; c) all speakers (mono- or bilingual) have non-linguistic ways of improving executive function; and d) benefits from bilingualism – and all cognitively challenging activities – are inconsistent because individuals vary in the number and kinds of experiences they have that promote superior executive function.

Keywords: bilingualism and executive function, bilingualism and dementia, improving executive function, improving aging

The focus of this keynote is the cognitive benefits of bilingualism. "Bilingualism" should be understood to include knowledge of any number of languages beyond one. Section 1 examines "executive function"[1], the main cognitive benefit of interest, and "cognitive reserve", or intact cognitive abilities despite neural damage. Section 2 examines the benefits of bilingualism and other "challenging" experiences for executive function and for protection from dementia. Section 3 summarizes where we are now.

Without understanding the components of executive function, the ways that executive function is measured, the relation between superior executive function and delay of cognitive decline, and the variety of experiences that are linked to improved executive function and cognitive reserve, it is not possible to assess the cognitive benefits of knowing or using more than one language.

With respect to bilingualism, I see two logical possibilities.

1. There *is* a benefit of bilingualism for executive function, but that benefit competes with other benefits that both mono- and bilinguals have to varying degrees. Depending on the composition of each group in any given experiment, the other benefits may be more plentiful in the monolingual than bilingual group (or sufficiently plentiful in both groups), so that the benefits of bilingualism are invisible. This is the possibility that I favor.
2. There is *no* cognitive benefit of bilingualism. In experiments that have found a benefit, the effect is either due to the accidentally larger number of other positive factors, such as high SES, that bilinguals have in that particular sample, or due to the correlation of bilingualism with some other active property that is difficult to separate from bilingualism.

Three sets of facts lead me to favor possibility one (although possibility two has had a number of proponents, e.g., Hilchey & Klein, 2011; Paap & Greenberg, 2013). First, as Section 1 presents in detail, executive function has different components. Depending on the tasks we use to measure executive function, one or another component

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[1] Although "executive function" is singular, the referent is plural. I will use the singular with the understanding that it refers to multiple processes.

may be primary[2]. Relatedly, tasks that tap executive function also inevitably tap other cognitive components that are not part of executive function, such as visual perception. It would be very surprising if a variety of cognitive experiences, including bilingualism, did not jointly affect performance on tasks measuring executive function.

Second, we already know that many different experiences are associated with superior executive function, delay of dementia, or both. In addition to language status (mono- or bilingual), factors include socioeconomic status; immigrant status; extent of exercise; presence of musical training; experience with action video games; education level; time spent in leisure activities; and, possibly, personality variables. There are no doubt other factors that have not yet been systematically investigated. Since managing two or more languages is a challenge, it would be very surprising if bilingualism were not among the challenging factors that contribute to superior executive function.

Third, in all cases, whether looking at language status or other variables, effects are somewhat inconsistent, but are generally positive when they do occur. No variable seems to trump any other variable.

It is the combination of the three sets of facts that accounts for the inconsistencies in findings. We know relatively little about executive function, relatively little about the tasks that are used to measure its components, and relatively little about the range of cognitively enriching experiences that exist. In any given study, participants have different sets of experiences, many of which cannot be controlled for or are unknown but on a par in their benefits with bilingualism. Further, those experiences interact with the tasks in unknown ways.

The range of executive functions, the range of tasks measuring executive function, and the range of experiences that are associated with superior executive function raise an important question about mechanism. Is there a single mechanism or several different mechanisms underlying superior executive function? If executive function is manifold, if different tasks measure different aspects of it, and if different experiences give rise to better or worse performance on those tasks, it seems likely that there are several different underlying mechanisms. If that is correct, future research should identify the different mechanisms rather than search for a single mechanism.

Early explanations for the bilingual advantage in cognitive tasks focused on the inhibition that balanced bilinguals who use each language frequently must exercise in order to prevent the inappropriate language from intruding (e.g., Green, 1998). Not only is there evidence that both of a bilingual's languages are involved at the lexical level (Kroll, Bobb, Misra & Guo, 2008), but there is also evidence of interference at the syntactic level (e.g., Hatzidaki, Branigan & Pickering, 2011; Hsin, Legendre & Omaki, 2013; Kroll, Dussias, Bogulski & Valdes Kroff, 2012; Runnqvist, Gollan, Costa & Ferreira, 2013). Since interference is not usually apparent in bilinguals' speech, that suggests that bilinguals successfully inhibit their irrelevant language(s).

Given the wide range of activities that lead to superior cognitive function, an explanation that relies on inhibition is obviously insufficient. Musical training, active video game playing, exercise, and other enriching experiences may involve inhibition, but, as with exercise, other processes appear more dominant. (For somewhat different reasons, Bialystok, Craik & Luk, 2012, and Kroll & Bialystok, 2013, also reject reliance on inhibition.) Conflict monitoring has also been proposed (Bialystok et al., 2012), but some enriching experiences do not involve conflict monitoring in any obvious way. Use of a more global term – mental flexibility – would reflect a continued search for a single mechanism (Bialystok et al., 2012; Kroll & Bialystok, 2013; Peal & Lambert, 1962). I propose going in the other direction. There is no single underlying mechanism, but many underlying mechanisms, likely including inhibition and conflict monitoring, as well as others.

If so, a many-many-many-many relation holds among executive function, tasks, experiences, and mechanisms. Executive function is many-faceted: it includes planning, inhibiting, shifting, and updating. Tasks measuring executive function measure multiple processes simultaneously, including processes that are not part of executive function, like response readiness. Multiple experiences, including bilingualism, support executive function. The underlying mechanisms are varied.

The idea that bilingualism is one challenge out of many has already been articulated with respect to cognitive reserve (the ability to maintain cognitive function despite brain pathology): "... bilingualism is a cognitively demanding condition that contributes to cognitive reserve in much the same way as do other stimulating intellectual and social activities" (Craik, Bialystok & Freedman, 2010). A similar point has been made about contributions to executive function (Hilchey & Klein, 2011). The guiding hypothesis of this paper is along those lines: consistent cognitive challenge, in any form, generally yields better performance on tests of executive function and generally yields more successful (i.e., less demented) aging. "Consistent cognitive challenge" is, of course, only a cover term that is not itself explanatory. It is not defined independently of the various experiences that demonstrate benefits in executive function, but is circular: experience x

[2] In that respect, our understanding of executive function is like the story of the people examining an elephant in the dark, each touching a different part. Each would draw a different conclusion about what the elephant is like, depending on whether they touch the trunk, a tusk, an ear, the tail, the side, and so on. The elephant of executive function has many different parts within one body.

is associated with superior executive function; therefore, it is cognitively challenging. At the moment, that cover term is the best that we can do.

I concentrate on behavioral studies because my aim is to understand the inconsistencies in cognitive outcomes. That bilinguals' brains are different from monolinguals' has been documented and discussed in multiple papers (see, e.g., Abutalebi, 2008; Abutalebi & Green, 2007, 2008; Barrett, Ashley, Strait & Kraus, 2013; Chang, 2014; Li, Legault & Litcofsky, 2014). Even individuals who acquire a second language in adulthood show changes in neural networks and, in some cases, in neuroanatomy as well, testifying to the brain's responsiveness to experience (Li et al., 2014). Other studies show brain changes in response to other types of cognitively challenging experiences among both young and old adults (Hötting & Röder, 2013). Just as there are inconsistencies in the behavioral outcomes, there are also inconsistencies in the neural outcomes and concern about possible artifacts. (For reviews, see Li et al., 2014; Lövdén, Wenger, Mårtensson, Lindenberger & Bäckman, 2013; Thomas & Baker, 2013.)

Craik (2006) points out that "cognitive processes depend on brain activities but are clearly not equivalent to them." It is possible to have different neural activities with similar behavioral outcomes. That is particularly apparent in research on brain differences among males and females, where brain differences are often not paired with behavioral differences (e.g., DeVries, 2004; Eliot, 2011; Fine, 2010), but the phenomenon has broad scope. Different neural networks can exist for mono- and bilinguals without the concomitant presence of behavioral differences. It may also be the case that some cognitive constructs, such as *g* (the 'general' factor in all IQ tests), have no direct neural correlates (Craik, 2006). Finally, the existence of individuals who are cognitively normal but have verifiable brain disease demonstrates that cognition can continue apparently unimpaired even in the presence of the neurofibrillary tangles and amyloid-β plaques characteristic of Alzheimer's (see, e.g., Driscoll & Troncoso, 2011).

1. Executive function and cognitive reserve

Executive function and the tasks that measure it

In order to assess the role of bilingualism on executive function, we need to know what executive function is. In essence, executive functions are those that manage, integrate, regulate, coordinate, or supervise other cognitive processes, such as attention and visual perception. A wide range of cognitive abilities and capacities is included and different researchers have proposed somewhat different repertoires. For example, it can include cognitive flexibility, inhibition, working memory, problem-solving, reasoning, and planning (Diamond & Lee, 2011). Cognitive flexibility is sometimes viewed as related to creativity (e.g., Diamond, 2012, 2013; Ritter, Damian, Simonton, van Baaren, Strick, Derks & Dijksterhuis, 2012). I will rely here on an analysis of executive function based on latent variable analysis: it separates executive function into two specific factors – *updating* and *shifting* – and a factor that is common to both of them (Miyake & Friedman, 2012). This analysis supersedes an earlier proposal (Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000) that specified three factors – inhibition, updating, and shifting. *Inhibition* was dropped because tasks measuring inhibition show no distinct variance that is not captured by the common factor variable.

Although executive function cannot be equated with any particular task or set of tasks, it is always inferred via performance on a task. Most tasks involve several executive functions as well as other processes. Appendix 1 (see Supplementary Material, Appendix 1) contains links to on-line demonstrations and descriptions of different tasks that are frequently used to measure one or another aspect of executive function so that readers can familiarize themselves with the tasks by actually trying to perform them. Reading about the tasks cannot convey the range of processes and mechanisms that the tasks draw on for successful completion, what it is like to participate in the tasks, or what makes a task easy or difficult. Most tasks also exist in a range of versions, but only one example of each task has a link in Appendix 1.

The common factor – inhibition by another name?

The "common factor" thought to underlie all examples of executive function is "about one's ability to actively maintain task goals and goal-related information and use this information to effectively bias lower-level processing" (Miyake & Friedman, 2012, p. 11). Tasks that require delay of gratification exemplify the common factor. A child, for example, may be told that if she refrains for 30 seconds from eating a marshmallow that is right in front of her, she will later receive two marshmallows; or, if she does not touch an attractive toy for 30 seconds, she will be able to play with it at the end of that time. The child must keep in mind the fact that a larger reward will be hers if she can wait, and use that information to prevent herself from reaching out and taking the lesser reward. *Anti-saccade tasks* (Supplementary Material, Appendix 1, Section 1.), *Stroop tasks* (Supplementary Material, Appendix 1, Section 2.), and *stop-signal tasks* (Supplementary Material, Appendix 1, Section 3.), like delay of gratification, were first considered to be examples of tasks that tap inhibition; in the new analysis they are considered to tap the common factor (Miyake & Friedman, 2012).

Since the correlation between inhibition and the common factor is almost perfect (Miyake & Friedman, 2012), one could gloss the common factor as the ability to inhibit inappropriate responses (see e.g., Zacks & Hasher, 1994) and propose inhibition as the factor that is common to updating and shifting.[3] One advantage of explicitly labeling inhibition as the factor common to all examples of executive function is that it is somewhat more informative about the possible underlying mechanism than is the "ability to actively maintain task goals and goal-related information and use this information to effectively bias lower-level processing" (Miyake & Friedman, 2012, p. 12). The more abstract definition, however, has the advantage of being general enough and flexible enough to be seen as a factor in most tasks. Carrying any task through to completion will require one to maintain task goals and to bias lower-level processing that might otherwise prevent the attainment of those goals.

Updating

To turn now to the specific components, *updating* is required in tasks, like the letter memory task, or n-back tasks in general, that require the participant to constantly refresh the material in working memory. (See Section 4 in Supplementary Material, Appendix 1, for a challenging version of an n-back task.) Updating might be glossed as "effective gating of information" or "controlled retrieval from long term memory" (Miyake & Friedman, 2012); or as working memory (Hoffman, Schmeichel & Baddeley, 2012); or as a form of executive attention, "the ability to control attention to maintain information in an active, quickly retrievable state" (Engle, 2002, p 20). Inhibition and updating show different neural patterns and different patterns with aging (Turner & Spreng, 2012).

Shifting

Shifting is construed as "flexibility – ease of transitioning to new task-set representations" (Miyake & Friedman, 2012). A task that reflects shifting is a *color-shape task* in which participants shift from responding on the basis of color or shape. (See Section 5 in Supplementary Material, Appendix 1 for a color-shape task.) Other forms of task switching involve other dimensions, such as judging numbers either on the basis of whether they are odd or even or on the basis of whether they are greater or smaller than 5.

Unclassified tasks

Three other tasks – the *Simon task* (Simon & Wolf, 1963), the *flanker task*, and the *ANT (Attention Network Task)* – have been used frequently in bilingualism research. In the *Simon task*, the participant sees a red figure (e.g., a rectangle) and must press a key on the right side of the keyboard, or a blue figure and must press a key on the left side of the keyboard. Sometimes the placement of the color on the screen corresponds to the side of the keyboard where the participant must press a key (congruent trials) and sometimes the placement is on the other side (incongruent trials). See Section 6 in Supplementary Material, Appendix 1 for an on-line demonstration of a Simon task.

In the *flanker task*, a participant typically sees an array of 5 stimuli, commonly arrows. The participant is asked to respond based on the direction the central arrow is pointing. On some trials that arrow is flanked either by arrows pointing in the same direction (congruent, or no-conflict, trials) or arrows pointing in the opposite direction (incongruent, or conflict, trials). The participant's task is to press a key on the right side of the keyboard if the arrow is pointing right and a key on the left side of the keyboard if the arrow is pointing left. The flanker task can be made more complicated by including a go/no-go component. See Section 7 in Supplementary Material, Appendix 1 for an online version of the flanker task. A related task is the *Attention Network Task, or ANT*. The ANT involves more processes than the flanker task – alerting and orienting in addition to executive function. See Section 8 in Supplementary Material, Appendix 1 for an online version of the ANT.

Yet other tasks have been used to measure executive function. See Section 9 in Supplementary Material, Appendix 1 for short descriptions. The use of so many different tasks makes comparisons across experiments difficult. All the tasks measure slightly different aspects of executive function as well as different ancillary processes, so the implications of failures to achieve consistent benefits across tasks cannot be readily assessed. Nor, for that matter, can the implications of success in achieving consistent benefits.

In most studies, experimenters subtract the mean reaction time on congruent (or control) trials from the reaction time on incongruent trials, in order to obtain a measure of the cost of incongruency. Or one subtracts the mean reaction times for trials where no switch is required from trials where a switch is required.[4]

[3] Earlier work (Miyake et al, 2000) showed that the latent variable of inhibition was highly correlated with the latent variables of updating (.77) and shifting (.79), while updating and shifting were not strongly correlated with each other (.38).

[4] The assumption is that, since reaction time is measured in an interval scale, a 20 ms difference among participants who average 300 ms overall is equivalent to a 20 ms difference among participants who average 1000 ms overall. That assumption may, however, be incorrect. One way of adjusting for overall speed differences among participants is to use a proportional score (dividing the difference in reaction time by the reaction time for the congruent or no-switch trials) to compare young and old mono- and bilinguals, who have very different reaction times (Gold, Kim, Johnson, Kryscio & Smith, 2013). Another possibility is to conduct regression analyses, using incongruent reaction time as the dependent variable and congruent

Task impurity

Tasks are "impure" (Burgess, 1997; Friedman, Miyake, Young, DeFries, Corley & Hewitt, 2008; Marton, Campanelli, Eichorn, Scheuer & Stepanoff, 2013, among others) or, more neutrally, tasks have multiple components. No task measures just one process. Even tasks that are superficially similar, such as the Simon and the flanker, require different cognitive, perceptual, and motor mechanisms. That is evident when one acts as a participant in various tasks.

Consider the Simon and flanker tasks from the point of view of their similarities and differences. Both tasks require the participant sometimes to use one finger and sometimes a different finger in responding. Both tasks have congruent and incongruent trials. The similarity stops there. The stimuli are different – rectangles vs arrows; one is non-directional and the other is inherently directional. More important, the incongruency in the flanker has a different source from the incongruency in the Simon. In the flanker, incongruency is due to a conflict between the direction of the target arrow in the *focus* of attention and the direction of the arrows in the *periphery* of attention. The congruent item is focal and the incongruent surround is peripheral (Guiney & Machado, 2013). The flanker requires one to ignore the arrows surrounding the target. In the Simon, incongruency is due to a lack of alignment between the spatial position of the stimulus and the spatial position of the key to be pressed. There is a single stimulus and it is always in the participant's focal attention whether it is congruent or incongruent. Another difference is that the Simon requires inhibition of a prepotent response whenever the stimulus is on the other side of the screen from the keyboard response, while the flanker does not (Poarch & Van Hell, 2012).

Although the task differences might seem minor, they have consequences. Average reaction time, independent of congruency condition, correlates well between the Simon and flanker tasks: people who are fast overall on the Simon task are fast overall on the flanker task. But the cost of incongruency does not correlate well between the two tasks. Individuals who show a low cost of incongruency on the Simon do not show a similarly low cost on the flanker (e.g., Humphrey & Valian, 2012; Paap & Greenberg, 2013; J. Van Hell, personal communication, 30 Dec 2012). Even the verbal and numerical versions of the Stroop do not correlate significantly with each other (Duñabeitia, Hernández, Antón, Macizo, Estévez, Fuentes & Carreiras, 2014). Since the tasks are conceptually extremely similar, it is likely that cognitive processes outside of executive function are responsible for the differences in responding. As a result, it is difficult to know whether differences, when they are found, are due to the aspects of a task that measure executive function or to aspects that measure other cognitive processes.

Now consider the ANT. It includes alerting and orienting components in addition to a conflict component (Supplementary Material, Appendix 1, Section 8.); the conflict component is similar to that in a flanker task. The alerting and orienting components are not specifically tapping executive functions. Active video game players, who show superior performance on many tests of visual performance and attention, perform better than non-game players on the alerting component. When tested on the ANT, participants in four age groups (7-10, 11-13, 14-17, 18-22) were always faster than non-gamers, but showed a greater cost of incongruency than did non-players (Dye, Green & Bavelier, 2009). This effect may be due to the greater spatial attentional span that active video game players have (Dye et al., 2009). Because players can take in more peripheral stimuli at one time than non-players can, they have an advantage in active video game play. But they have a disadvantage in disattending to the flanking stimuli; their wider attentional purview results in their seeing the conflicting arrows and being slowed down by the conflict. Whether or not that explanation (of the counter-intuitive handicap which video game players experience on incongruent conditions) is correct is less important than the possibility it suggests: cognitive processes that lead to superior performance in some domains can lead to inferior performance in other domains, even if all the domains in question tap one or another aspect of executive function.

In the flanker task in Appendix 1, the central arrow is sometimes smaller than the surrounding arrows, sometimes the same size, and sometimes larger. I found the condition with the smaller arrow easy to respond to, even in the incongruent trials, because there were small blank spaces on either side of the arrow, drawing my attention to the arrow and making it easier to ignore the flanking arrows. That type of visual effect is not itself an executive function process, but it interacts with an executive function process. We need fine-grained task analyses in order to understand what processes are being recruited and how they interact.

Summary of executive function

The brief review demonstrates how much there is still to understand about what the components of executive function are, how those components interact with other cognitive processes (such as alerting and orienting), and how to measure those components. Good performance on one executive function task does not entail good performance on other executive function tasks. Rather small changes in the format of an experiment may alter the

reaction time and language status as the independent variables – along with other measures frequently taken, such as age, gender, socioeconomic status, verbal scores, and general cognitive ability scores. The consequences of using different data analytic procedures when comparing mono- and bilinguals have not been systematically investigated. A comparison of results using different data analytic procedures would be very helpful.

patterns of results, and what seem at first blush like minor differences between tasks may instead be sufficiently major that performance on one does not correlate with performance on another.

I draw three implications from the discussion thus far. One is that it will be difficult to make clear predictions about the benefits of cognitively enriching activities, including bilingualism. A given experience may affect one task one way and another task another way. Further, not all ways of being bilingual, or of being musically trained, need be the same; someone who uses all their languages frequently, even if one of them is newly acquired, may differ from someone who uses their non-dominant languages infrequently, even if one of them was their mother tongue. The second implication is that small variations in task components can change whether participants do well or badly on a task, even if those components are orthogonal to executive function. The third is that we should expect inconsistencies from experiment to experiment not only because of our still fragmentary understanding of executive function and the tasks used to measure it, but also because no experiment can control for, or measure the effects of, every experience that improves or enriches high-level cognitive functioning.

Cognitive reserve and executive function

Researchers who examine aging often speak of "cognitive reserve". The term refers to the fact that some individuals with clear neural damage or impairment nevertheless function well in everyday life and perform well on cognitive tests for some period of time (see review in Tucker & Stern, 2011). Depending on the study, somewhere between 30% and 50% of individuals whose brains at autopsy demonstrate evidence of Alzheimer's were nevertheless functioning normally at the time of their death, suggesting that many people have qualities that protect them from neural damage. Education, IQ, vocabulary, physical fitness, number of leisure activities, number of social activities, and other factors are often used as proxies for cognitive reserve, since individuals with those characteristics resist neural damage better (Tucker & Stern, 2011). (In addition, some people seem to have better-maintained brains than others, Nyberg, Lövdén, Riklund, Lindenberger & Bäckman, 2012.) As research continues, more enriching experiences may come to light.

Stern (e.g., 2002, 2009, 2012) has suggested that there are at least two ways, not mutually exclusive, that cognitive reserve could operate. One way is more efficient use of neural pathways; another is compensatory development of neural pathways that are not initially associated with a task. There is some evidence in favor of each (Tucker & Stern, 2011). Although individuals with higher education and occupational level are slower to show signs of cognitive decline, once they do show clear signs, they decline more rapidly than individuals with less education and lower occupational levels and they die sooner (Amieva, Mokri, Le Goff, Meillon, Jacqmin-Gadda, Foubert-Samier, Orgogozo, Stern & Dartigues, 2014; Stern, 2012, but see Zahodne, Glymour, Sparks, Bontempo, Dixon, MacDonald & Manly, 2011). That suggests that there comes a point when efficiency and compensatory mechanisms can no longer overcome the increasing neural deterioration.

It seems to make sense that whatever contributes to better executive function will also protect against cognitive decline, and vice versa. And there are experiences that are associated with both (as will be reviewed later). But there are also dissociations. Whatever it is about leisure activities, for example, that leads to cognitive reserve, it may not be related to what leads to superior executive function. (It is, of course, an empirical question.) The converse may also be the case. Another reason to be cautious about linking executive function and cognitive reserve is that much hinges on how the concepts are measured. The extent of overlap between cognitive reserve and executive function will change depending on what tests are used to measure each construct.

A third reason for caution is that heterogeneous mechanisms may be involved in cognitive reserve. 'Cognitive reserve' is a much less well understood concept than executive function. With respect to executive function, Miyake & Friedman (2012) speak of unity (the common factor) and diversity (the individual factors of shifting and updating). Executive function may be diverse, but its contours have been laid out and its parts have been at least initially described. With respect to cognitive reserve, only the diversity is obvious. "Cognitive reserve" is the name of a phenomenon rather than an explanatory term. It is defined purely with respect to an outcome – ability to withstand neural damage.

2. Contributors to better executive function and non-demented aging

Contributions of enriching experiences to executive function

In measuring executive function or cognitive decline, it is often difficult to know whether individuals are antecedently different and have engaged in the activity that correlates with executive function because they have superior executive function to begin with, or whether the experiences in question played a causal role in improving executive function. In music training, for example, where results are somewhat equivocal, individuals who study music may be antecedently different – in personality or cognition or both – from individuals who do not study music. Two siblings can both be required to take piano lessons, but one of them may practice as little as possible and quit as soon as possible. Would the sibling who quit have benefitted in executive function by continuing to study music? Or does the training only benefit those who want to continue it? Similarly, individuals who play action video games may have antecedent traits that distinguish them from individuals who do not. Benefits that appear to accrue to music training or active video game playing may actually accrue to personality or cognitive properties of people who begin and continue those activities.

A propensity to seek cognitive enrichment may be what unifies the effects of some of the many different activities that are related to executive function. In that case, what matters is the individual's proclivity toward challenge rather than the particular form of the challenge that they choose. Only in studies where individuals are selected from similar populations and randomly assigned to intervention groups, and where attrition rates are equal between the experimental and control groups, can one establish a causal relation between the training experience and the superior executive function. Relatively few training studies meet all the criteria.

Unlike participation in some cognitively challenging experiences, individuals in many communities do not typically choose to become bilingual but are born into bilingualism (Bialystok et al., 2012). Bilingualism in many countries is a challenge imposed on community members as a whole rather than a challenge that a subset of individuals seeks or that some parents may impose. In some communities and families, however, choice may play a role. In the United States, for example, some children refuse to respond, or are not required to respond, in their non-English language. Life-long balanced bilinguals who live in a country like the United States "choose" to use their non-English language frequently; others, initially reared similarly, "choose" not to remain actively bilingual as they grow up.

The following subsections discuss effects of bilingualism and other activities on executive function and cognitive decline. I concentrate on bilingualism, but also briefly review education, exercise, music experience, active video game experience, socioeconomic status, and miscellaneous factors. Inconsistencies exist for all factors.

Bilingualism

The effects of bilingualism on executive function, and the inconsistencies in those effects, have been extensively reviewed (e.g., Adesope, Lavin, Thompson & Ungerleider; 2010; Bialystok, 2011; Bialystok et al., 2012; Costa & Sebastián-Gallés, 2014; Hilchey & Klein, 2011; Kroll & Bialystok, 2013; Paap, 2014). Selective reviews also appear in most reports of empirical findings. Two different meta-analyses have come to different conclusions. Adesope et al. (2010), for example, concluded that the effect size in favor of a bilingual advantage for what they called attentional control, which is similar to executive function, was the largest of all the effect sizes they calculated. At the same time, it, like the other categories of analysis (e.g., metalinguistic awareness), was highly heterogeneous. Since only 14 studies were included under the heading of attentional control, moderator analyses on attentional control alone could not be conducted. A later analysis (Hilchey & Klein, 2011) of studies using the Simon or flanker tasks, concluded instead that monolinguals and bilinguals did not differ with respect to the interference, or incongruency, effect (incongruent trial reaction times minus congruent trial reaction times).

Inconsistencies abound across studies and within studies. Some studies report robust differences between mono- and bilinguals while others report none. Studies that include a battery of executive function tasks tend to find benefits of bilingualism only for some of the tasks (e.g., Poulin-Dubois, Blaye, Coutya & Bialystok, 2011) or only for some types of trials within tasks (e.g,. Bialystok, 2006). I have argued that inconsistencies should be expected because of the uncertainty about what components of executive function different tasks tap, and uncertainty about the importance of task features that are orthogonal to executive function. Another reason to expect inconsistencies is that all the effects may be relatively small. In that case, one would not expect every task to show an effect (Carter & McCullough, 2013). (See Cumming, 2014; Morey, Rouder, Verhagen & Wagenmakers, 2014; Funder, Levine, Mackie, Morf, Vazire & West, 2013, and related papers for recommended standards in experimentation and data analysis.)

There is so much variation from study to study in tasks (e.g., Simon vs Stroop), task versions (e.g., verbal vs numerical Stroop), and measures within those tasks (e.g., accuracy rates vs reaction times vs reaction times only for certain types of trials), that it is very difficult to determine the locus of inconsistencies (Paap, 2014). If apparently small differences in task, experimental design, sample selection, or data analysis turn out to matter, that demonstrates a need for a much finer grained exploration of the cognitive processes at work.

Children

Studies of children with large samples have tended to show weaker effects, or no effects, compared to studies with small samples (but the size of the samples is somewhat diluted by the number of different ages and conditions.) For instance, three large studies comparing mono- and bilingual children have failed to find benefits of bilingualism (see Supplementary Material, Appendix 2, for details). In comparisons between monolingual Spanish-speaking and bilingual Spanish–Basque speaking children, there were no bilingual advantages on the ANT, the verbal Stroop, or the numerical Stroop (Antón, Duñabeitia, Estévez, Hernández, Castillo, Fuentes, Davidson & Carreiras, 2014, total n = 360); Duñabeitia et al., 2014, total n = 504). Participants did show a cost of incongruency, and younger children showed a stronger cost than older children, so the tasks measured what was intended. But there were no differences in the incongruency effects as a function of language status. Both studies controlled for a range of possibly confounding variables. Further, the size of the incongruency effect in the verbal Stroop was not correlated with the size of the incongruency effect in the non-verbal Stroop. Although both tasks tap similar executive functions, for which the difference between words and numbers is irrelevant, it matters enough to change the pattern of responding.

The third large study compared monolingual English-speaking and bilingual Welsh–English speaking children, teenagers, young adults, and older adults from Wales and England (Gathercole, Thomas, Kennedy, Prys, Young, Viñas Guasch, Roberts, Hughes & Jones, 2014, total n = 650). On neither a card-sorting task nor a Simon task were there accuracy or reaction time advantages favoring bilinguals within any age group (except for accuracy among old adults); a few favored monolinguals. This study did not, however, control for possible confounding variables.

Among the experiments showing beneficial effects of bilingualism in children is a study comparing 7-month-olds who were exposed only to Italian with 7-month-olds exposed to both Italian and another language (usually Slovenian – Kovács & Mehler, 2009). The infants learned to associate either an auditory or visual pattern with a visual reward. When the contingencies for the reward were switched, the infants exposed to two languages accommodated the switch more rapidly. Since the bilingual infants had accumulated only minimal exposure to their two languages and were not yet speaking, their superior executive function performance could not be due to experience in inhibition of one language or conflict monitoring of the two languages (Bialystok, 2010). The challenge of listening to two different phonologies and prosodic patterns may be sufficient to improve executive function. One might then expect that 7-month-olds who heard both German and Dutch would not show a benefit, given the close overlap between the two languages.

A limited benefit of bilingualism has been reported for bilingual two-year-olds who are still on the cusp of language learning (Poulin-Dubois et al., 2011). Of 5 tasks (see Supplementary Material, Appendix 2), bilinguals had a higher proportion of correct trials on a shape Stroop task, but not on delay or switch tasks. Since bilingual 7-month-olds show benefits on a switch task, it is not clear why the bilingual 2-year-olds in this study did not. Slightly older children, aged 3 in one group and 4½ in another, showed more consistent benefits of bilingualism (Bialystok, Barac, Blaye & Poulin-Dubois, 2010), perhaps suggesting that more language experience is needed before effects are visible. Out of four tasks (see Appendix 2 for descriptions), bilingual children performed better on all but the ANT.

An interesting comparison of 4-year-olds who were Korean–American bilinguals, Korean–American (English-speaking) monolinguals, Korean monolinguals, or non-Korean–American (English-speaking) monolinguals was designed to separate language effects from culture effects (Yang, Yang & Lust, 2011). The bilingual group was more accurate and faster overall compared to the three monolingual groups on all conditions of a child version of the ANT, suggesting that language status was more important than culture, and also suggesting a general advantage to being bilingual. Visual inspection of the means suggests that the bilingual group showed a smaller incongruency effect with respect to accuracy, as one would predict, but a larger effect with respect to reaction time, contrary to what one might predict.

For slightly older children, ranging in age from 5 to 8, there are reaction time benefits of trilingualism on the incongruency effect of Simon task, compared to monolinguals, and benefits of both bi- and trilingualism on the incongruency effect of the ANT, compared to second language learners (Poarch & Van Hell, 2012; see Appendix 2 for fuller description). Here, the benefits are seen for reaction time but not accuracy.

While at least one study has suggested that, in children, apparent benefits of bilingualism are due to correlated SES differences (Morton & Harper, 2007), another has found that SES and bilingualism independently contribute to more accurate (though not faster) flanker performance in children aged 6 and 7 (Calvo & Bialystok, 2014; see Appendix 2 for details). Only overall performance is reported, not performance on incongruent vs congruent trials. Since bilinguals showed superior performance across the board, they may be more accurate in general rather than have better executive function.

Summary and interpretation of data on children

For children, effects are mixed across and within studies. Some studies show no benefits of bilingualism and others show benefits that are localized to particular tasks, components of tasks, or particular measures (e.g., accuracy or reaction time, but not both). The multiplicity of different tasks makes it difficult to isolate the source of the differences (Paap, 2014; Paap & Greenberg, 2013).

A concentration on bilingualism, instead of the range of experiences that improve executive function, makes it difficult to know what participant features to control for. When no differences are observed between mono- and bilingual participants, we are in the dark about what properties the monolinguals have that might make them and bilinguals perform similarly. Monolingual and bilingual children in a particular study might get different amounts of exercise, or some other beneficial experience. In addition, the lack of a thorough-going analysis of tasks measuring executive function means that we do not know to what extent task properties that are independent of executive function are overwhelming task properties that more directly reflect executive function. Finally, the overall benefits of bilingualism reported in some experiments may signify a global benefit rather than one limited to executive function.

Young adults

Especially when young adults are tested, effects have been inconsistent, with a number of reports of failure to find differences between mono- and bilinguals (see, e.g., the reviews previously mentioned in the beginning of the bilingualism section; studies cited in Paap, 2014). Two studies with large numbers of participants failed to find any benefits of bilingualism. One found no bilingual benefits for the Simon or flanker (Humphrey & Valian, 2012); the other found no benefits for the Simon, the flanker, a color-shape switching task, or an anti-saccade task (Paap & Greenberg, 2013). In neither study did the size of the incongruency effect correlate between the Simon and the flanker.

Earlier studies have varied, sometimes finding no or limited benefits on the Simon, flanker, and ANT, and sometimes finding strong benefits. In one modified version of the Simon, using arrows instead of rectangles (see Supplementary Material, Appendix 2 for details), young bilingual adults averaging age 20 showed no advantage (Bialystok, Craik & Luk, 2008). If anything, the bilinguals showed a larger incongruency effect (22 ms) than the monolinguals did (8 ms). (In contrast, old bilingual adults did show an advantage over monolinguals, though that was because they showed no incongruency effect at all.) Catalan–Spanish bilinguals have shown an advantage on the flanker, but only in cases where high-monitoring was required (Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009).

Stronger results with the ANT are apparent in a study comparing 20-year-olds who were early- or late-learning Spanish-English bilinguals. Both types of bilinguals outperformed monolinguals on the ANT (Pelham & Abrams, 2014), suggesting that the benefits of bilingualism, when found, are not restricted to those with a great deal of experience in their second language. Similarly, a comparison of Chinese students (average age 20, range from 18–48) who had learned English either early or late also found benefits for both types of bilinguals on a version of the ANT (Tao, Marzecová, Taft, Asanowicz & Wodniecka, 2011).

Another study compared second language learning students who were immersed in a second language learning environment with classroom learners; the classroom learners showed *more*, rather than less, of a benefit on the Simon, or were similar (Linck, Hoshino & Kroll, 2008). Similarly, less proficient bilinguals, as measured by reaction times to recognize translation equivalents, showed *more*, rather than less, of a benefit on the Simon or were similar (Linck et al., 2008). Thus, learning a second language, or being proficient in two languages, conferred a benefit in executive function compared to bilinguals, but degree of immersion or proficiency was irrelevant.

One study has found that early, but not late, bilingual college students (average age = 21) showed an advantage in the flanker task compared to monolinguals (Luk, De Sa & Bialystok, 2011). Age of bilingualism was operationalized as the time when individuals began using both languages on a daily basis; that was age 5 for early bilinguals and age 16 for late bilinguals. There was also a weak ($r = 0.24$) but significant correlation between age of active bilingualism and size of the flanker effect: the later the age at which participants began using both their languages actively, the greater the cost of conflict. On a measure intended to be similar, only bilinguals who rated themselves as 4 or 5 (on a 5-point scale) in speaking and listening in both childhood and adulthood were compared with monolinguals (Humphrey & Valian, 2012); there were no advantages for bilinguals so defined on either the Simon or the flanker task.

If frequent use of both one's languages is an important variable, then interpreters should show a greater benefit on a task like the Simon than garden-variety bilinguals. Spanish-speaking monolinguals, Spanish–English-speaking bilinguals, and Spanish–English-speaking interpreters were compared on the Simon, but all three groups performed similarly (Yudes, Macizo & Bajo, 2011). Thus, in general, it is difficult to find advantages in executive function for being a highly proficient bilingual; the simple challenge of dealing with two languages at any level appears to be cognitively enriching enough in the cases where advantages for bilingualism are found.

Overall, then, benefits of bilingualism are sparse on the Simon, flanker, and ANT tasks. Depending on one's task analysis, the Simon, flanker, and ANT may not be the best tests of bilingual benefits. On one analysis, the Simon primarily involves inhibition (Yudes et al., 2011), while on others it primarily involves interference (e.g., Bialystok et al., 2008). Absent a fine-grained analysis of tasks, it is not possible to determine whether one or another aspect of executive function is primary. On the face of it, the Simon, flanker, and ANT involve all three executive functions – inhibition, updating, and shifting. On a Stroop task, which can be interpreted as either an inhibition task (e.g., Heidlmayr, Moutier, Hemforth, Tanzmeister & Isel, 2014) or an interference task (Bialystok et al., 2008), there are bilingual advantages (Bialystok et al., 2008; Heidlmayr et al., 2014). Go/no-go tasks, in which participants must refrain from responding on some trials, might appear to be the best example of an inhibition task. In one experiment, participants had to press the space bar for any digit except the digit 3, in which case they were not to respond. Error scores – responding on no-go trials – were equivalent for mono- and bilinguals in both younger and older age groups (Bialystok et al., 2008).

Switching tasks like card-sorting and the color-shape task, almost by definition, highlight shifting, even if they also involve inhibition and updating. Shifting, or switching, might be seen as similar to what some bilinguals do as a matter of course – shifting from one language to another depending on contextual demands. If the conversational context is uniformly in one language, primarily inhibition of the other language(s) might be required, but in a translation environment, both shifting and inhibition would be required. Thus, one might predict that shifting or switching advantages would be reliably found in individuals who use both their languages regularly.

On a card sorting task, interpreters generally outperformed both mono- and bilinguals, who did not differ between each other (Yudes et al., 2011). (All three groups were equivalent in the number of categories they succeeded at, but interpreters were more efficient in arriving at those categories, making fewer attempts and fewer errors.) Thus, even though interpreters were equivalent to mono- and bilinguals in the Simon task, they outperformed both mono- and bilinguals in card-sorting. This study is like others in not showing differences between mono- and bilinguals among young adults.

Bilingual advantages have been reported in another shifting task, the color-shape switching task (Prior & MacWhinney, 2010; see Supplementary Material, Appendix 2). When trial sets were blocked – only color or shape was required – monolinguals and bilinguals responded with equivalent reaction times. In the mixed condition, where color and shape were each sometimes required, depending on the trial, (or the reverse), monolinguals were slower than bilinguals (Prior & MacWhinney, 2010). But a switching advantage for bilinguals is not generally found (e.g., Paap & Greenberg, 2013), even among bilinguals who frequently use two related Romance languages, Spanish and Catalan (Hernández, Costa, Fuentes, Vivas & Sebastián-Gallés, 2010; Hernández, Martin, Barceló & Costa, 2013). One might expect that managing two similar languages would be more difficult than managing two very different languages, because of the phonological, lexical, and grammatical interference between similar languages. But across three experiments using a version of a color-shape task, there were no advantages in switching among bilinguals (though they were faster overall; Hernández et al., 2013).

Further, bilinguals' performance on language switching tasks does not always parallel their performance on cognitive switching tasks (e.g., Calabria, Hernández, Branzi & Costa, 2011; Calabria, Branzi, Marne, Hernández & Costa, in press; Weissberger, Wierenga, Bondi & Gollan, 2012). That is, bilinguals are better – make fewer mistakes – when switching between languages than when switching on cognitive tasks, a point discussed at greater length in the section on older adults.

Summary and interpretation of data on young adults

Especially among young adults, it is common to find no differences between mono- and bilinguals, but positive results also exist. My interpretation is that young adults have accumulated, and are in the midst of accumulating, many cognitively enriching experiences. The participants in most experiments with young adults are college students. We *hope* that they are being cognitively challenged. Although we do not know the full range of experiences that will improve executive function, the teenage and young adulthood years are periods of experimentation. In the welter of new experiences that require planning, updating, shifting, and inhibiting, it would not be surprising if positive effects of bilingualism would be washed out. Beneficial challenging experiences may include examples that have not yet been systematically studied. For example, an absorbing interest in American football (sometimes referred to as a coach's game because of the many strategies involved), ballet, acting, or cooking may be cognitively demanding and lead to the development of a range of skills.

My hypothesis is slightly different from claims that young adults are operating at peak processing capacity or are extremely efficient processors (e.g., Kroll & Bialystok, 2013). Yes, young adults have faster reaction times than either children or older adults, and reaction times begin their inexorable slowing around age 20 (Fozard, Vercruyssen, Reynolds, Hancock & Quilter, 1994). But, on my analysis, young adult monolinguals who perform on a par with bilinguals succeed not primarily because they are efficient processors, but because they have other experiences that are on a par with bilingualism in their ability to enrich cognitive functioning. A similar line of reasoning can be extended to children. They spend more time sleeping and may (arguably) also spend more time in unchallenging activities than do young adults, but they spend much of their waking time actively learning.

Older adults and executive function

It is with old and very old adults that the benefits of bilingualism for executive function seem clearest (though that may partly be a function of less research with this population). For example, one study found that middle-aged bilinguals between 30 and 60, as well as old bilinguals between 60 and 90, had a smaller incongruency effect in the Simon task than did age-matched monolinguals (Bialystok, Craik, Klein & Viswanathan, 2004). In some cases, reaction times differed by a factor of 2 or more. That finding is similar to another report that old bilinguals showed an advantage on a conflict version of the Simon and on a Stroop task (though not on a go/no-go task or a reverse Simon task, Bialystok et al., 2008).

In an examination of performance on a color-shape task, a comparison of middle-aged adults (average age, 32) and old adults (average age, 64) in two experiments found that old bilingual adults outperformed their monolingual peers in both experiments, while middle-aged bilingual adults did not show an advantage (Gold et al., 2013). Recall, however, that older Welsh–English bilinguals did not show an advantage on either card-sorting or the Simon task (Gathercole et al., 2014; see also Kousaie & Phillips, 2012, and Kirk, Scott-Brown & Kempe, 2013). A study of old Spanish-speaking immigrants found that bilingual status, when measured objectively, was associated with better executive function even though it did not reduce the likelihood of dementia (Zahodne, Schofield, Farrell, Stern & Manly, 2014).

Bilinguals' language system appears to be partially independent of their executive function system (e.g., Calabria et al., in press; Calabria et al., 2011; Magezi, Khateb, Mouthon, Spierer & Annoni, 2012). Several studies have compared bilinguals' ability to switch between their two languages and their ability to shift between color and shape. Aging affects language switching and color-shape switching differently among highly proficient Spanish-Catalan bilinguals. The cost of language switching does not appear to increase with age but the cost of color-shape switching does (Calabria et al., in press). In addition, for neither young nor old participants was there a correlation between the cost of language switching and the cost of color-shape switching. Both findings suggest that bilinguals' control over their languages is not mediated solely by executive function processes and that executive function is influenced by many different factors. Even when an increasing cost of switching languages with age is reported, there remains a dissociation with executive function; some elderly participants could not perform the color-shape task at all even though they could switch languages easily (Weissberger et al., 2012).

A dissociation between language use and executive function should not be surprising. Neither executive function nor language processing are monoliths. But the dissociation carries an interesting implication, namely that not all of the processes involved in managing multiple languages transfer to executive component processes. Skill in managing two languages does not completely transfer to the domain of executive functions. To some extent, systems are modular, even while they have more general effects.

Summary and interpretation of experimental data on older adults

The data overall, although mixed, suggest a benefit in older adults for being bilingual on tasks of executive function. Old adults, in contrast to young adults and children, might be expected to show more benefit from bilingualism because they tend to spend less of their time in active and challenging cognitive activities compared to young adults and children. In the absence of other stimulation, the benefits of bilingualism might be clearer.

Older adults and dementia

Although a natural hypothesis is that pursuit of any challenging cognitive activity will result in healthier aging, that is not a given. Dementia affects executive function but also cognitive systems like language and memory that are not executive functions. Thus, bilingualism might or might not have benefits for aging. The effects of bilingualism in slowing the onset of cognitive decline and dementia have been explored in a number of studies, starting with Bialystok, Craik, and Freedman (2007), who reported that bilinguals experienced dementia more than four years later than monolinguals.

Subsequent research has shown variation from study to study (Freedman, Alladi, Chertkow, Bialystok, Craik, Phillips, Duggirala, Raju & Bak, 2014). Some studies show benefits after equating participants on a range of variables (e.g., Alladi, Bak, Duggirala, Surampudi, Shailaja, Shukla, Chaudhuri & Kaul, 2013; Craik et al., 2010), while others do not (e.g., Zahodne et al., 2014).

Retrospective vs prospective studies

Studies that find a protective effect of bilingualism tend to be retrospective while studies that do not find a benefit tend to be prospective (Yeung, St. John, Menec & Tyas, in press; Zahodne et al., 2014). In an ideal world, the results from retrospective and prospective studies coincide. Unfortunately, the data on bilingualism are not ideal. In *retro*spective studies, individuals are consecutively tabulated according to the date at which they were diagnosed with a mild or severe cognitive impairment (often via the Mini-Mental State Examination, or MMSE) upon presentation at a memory clinic. Retrospective studies exhibit what could be called the complement class problem. Many individuals with cognitive difficulties never appear at a memory clinic and their characteristics are unknown; similarly, individuals without cognitive difficulties seldom appear at a memory clinic. Those individuals comprise the complement class. We only know the size and composition of the class that has visited the clinic, a class that may or may not be representative of the general population. Even if both mono- and bilinguals have comparable scores on the MMSE when they first appear in a clinic, and even if they decline at similar rates (Bialystok et al., 2007), the complement class could be different and thus change our conclusions about the total class.

In *pro*spective studies, in contrast, investigators study a large sample of a community and track their health over a period of years, generally between 4 and 10 years, noting changes in physical health, mental health, and cognition. Here, the whole class is examined, allowing an estimate of the incidence of a phenomenon. Although not everyone agrees to be a participant in such a study, and not everyone continues to participate, demographic comparisons suggest that those who enter and those who do not are similar. In prospective studies, individuals are usually not demented at the time of first being recruited or, if they are already demented, they are not included in the sample. Prospective studies use objective tests at each point along the way and thereby avoid the possibility of group-based differential sensitivity to symptoms of impairment.

Findings from retrospective studies

Retrospective studies tend to find that bilinguals experience dementia 4–7 years later than monolinguals, although the studies differ in their details (Alladi et al., 2013; Bialystok et al., 2007; Chertkow, Whitehead, Phillips, Wolfson, Atheron & Bergman, 2010; Craik et al., 2010; see review in Freedman et al., 2014), with some studies finding benefits when controlling for immigration status (Craik et al., 2010) and others not (Chertkow et al., 2010). For example, a study in Toronto, Canada, examined consecutive records from a two-year period of individuals who came to a memory clinic and received a diagnosis of probable Alzheimers disease (Craik, Bialystok & Freedman, 2010; see Supplementary Material, Appendix 2 for details). The average age at which families reported initial symptoms of cognitive decline was 72.6 for monolinguals and 77.7 for bilinguals. The average age at the first clinic visit was 76.5 for monolinguals and 80.8 for bilinguals. Both differences were significant, and were maintained after controls for covariates were introduced.

A later study comparing mono- and bilinguals in Toronto, Canada, with respect to both mild cognitive impairment and dementia, confirmed earlier findings that bilinguals presented with dementia at a later age than did monolinguals (in this study, about 7 years later), and also demonstrated a later onset of cognitive decline than monolinguals (about 4 years later; Bialystok, Craik, Binns, Ossher & Freedman, 2014; see Appendix 2 for details), even when controlling for immigration status and other factors.

In contrast, a study in Montreal, Canada, found that nonimmigrant *mono*linguals showed a later decline than nonimmigrant *bi*linguals; only nonimmigrants who were at least *tetra*lingual showed a protective effect (Chertkow et al., 2010; see Appendix 2 for details). For immigrants the findings were different. Immigrants had an overall earlier onset of cognitive impairment than nonimmigrants, (except for tetralingual nonimmigrants). Bilinguals, trilinguals, and tetralinguals were impaired significantly later than monolinguals. Because of the large number of variables in this study, and the differences in findings among nonimmigrants and immigrants, it is difficult to arrive at an overall interpretation. A retrospective study in Hyderabad, India, where immigration is not an issue, compared bi- and monolinguals (Alladi et al., 2013). Bilingualism was protective, even when covariates like education were controlled for.

One exception to the general finding with retrospective studies compared Spanish–English bilinguals in the United States. It investigated whether degree of bilingualism – measured as the extent to which participants were equal in their two languages on a naming task – was associated with delay of cognitive decline. It was, but only for low-education individuals; for high-education individuals there was no effect (Gollan, Salmon, Montoya & Galasko, 2011).

Summary and interpretation of data on cognitive decline and dementia in retrospective studies

Although there is variation from study to study, the retrospective studies show later decline for bilingual compared to monolingual individuals. In some cases knowing two languages is enough, in others it is necessary to know more than two. In one case, an advantage was found only for individuals with lower education, in others an advantage exists when education is controlled for. In one case, immigration status made a difference, but in others it does not. On the whole, the retrospective studies confirm a protective role for using more than one language.

Findings from prospective studies

Prospective studies, in contrast, tend to find that bilinguals and monolinguals show similar trajectories with respect to cognitive decline and dementia (Crane, Gibbons, Arani, Nguyen, Rhoads, McCurry, Launer, Masaki & White, 2009; Crane, Gruhl, Erosheva, Gibbons, McCurry, Rhoads, Nguyen, Masaki & White, 2010; Sanders, Hall, Katz & Lipton, 2012; Yeung et al, in press; Zahodne et al., 2014). For example, Crane et al (2010; see Supplementary Material, Appendix 2 for details) studied second generation Japanese–American men in Honolulu. Participants were divided into three groups: the monolingual group said they spoke or read no or very little Japanese; the middle group – 59% of the sample –

said they spoke but did not read or write Japanese; the bilingual group said they both spoke and read Japanese. Neither the mono- nor bilingual group differed from the middle group in their rate of cognitive decline.

A community-based prospective study of Hispanics in New York City similarly showed no difference in cognitive decline between Spanish–English bilinguals and Spanish monolinguals ranging in age from 64 to 95 (Zahodne et al., 2014). All the participants had been born outside the US and were assessed periodically over a period of up to 22 years, averaging 6.5 years. Language status was not associated with dementia once covariates for age at enrollment in the study, education, and sex of participant were included. For the subset of participants for whom objective English assessment scores were available, proficiency in English was also not associated with cognitive decline.

A notable exception to the failure to find a benefit of bilingualism in prospective studies is a study of a random national sample of Israelis who were tested three times over a 12-year period (Kavé, Eyal, Shorek & Cohen-Mansfield, 2008; see Supplementary Material, Appendix 2 for details). The participants were bi-, tri-, or at least tetralingual and had an average age of 83 in the first of three waves of data gathering. (The participants' advanced age in the first wave may be a factor in the findings.) All participants spoke at least Hebrew and at least one other language. The number of languages individuals spoke was an independent predictor of scores on a cognitive screening test at all three waves, and accounted for a significant increase in R^2 after age, gender, country of origin, education, and age of immigration to Israel had been entered as independent variables. The best scores were obtained by individuals speaking four or more languages (similar to Chertkow et al.'s 2010 findings). Educational level was a strong predictor, but even among individuals with more than 12 years of education, there was a dose response: the more languages the better. Thus, education and language status had independent effects.

Summary and interpretation of data on cognitive decline and dementia in prospective studies

Overall, community-based samples that follow individuals over time do not show advantages of bilingualism. Although there may be an issue regarding the extent of bilingualism of participants labeled bilingual (Freedman et al., 2014, note that Zahodne et al., 2014, did not have data on the age at which individuals became bilingual, and that Sanders et al., 2012, may have inadvertently included some bilinguals among their monolinguals), that seems less important than the methodological difference between retro- and prospective studies (Zahodne et al., 2014).

Summary and interpretation of data on old adults

With respect to measures of executive function, there is reason to think that elderly bilinguals show better performance than monolinguals. That conclusion is tentative, because there are fewer studies of executive function in the elderly compared to children or young adults. With respect to conversion to dementia, the safest conclusion thus far is that "bilingualism alone is insufficient to guarantee the postponement of dementia" (Freedman et al., 2014). The fact that most retrospective studies do show a benefit, while most prospective studies do not, is an inconsistency that needs to be resolved.

Education

The role of education is seen in an incidence study of 593 individuals with an average age of 74 who were not demented and were followed for up to 4 years. Over that time period, 106 were diagnosed as demented. Those with less than an 8th grade education developed symptoms of dementia at double the rate of those with more education. Similarly, those in low occupational categories experienced symptoms at double the rate of those in high categories (Stern, Gurland, Tatemichi, Tang, Wilder & Mayeux, 1994). Education also correlates with performance on executive function. For example, when cognitive reserve was measured as a composite of years of education, scores on the Peabody Picture Vocabulary Test, and the ability to correctly read aloud a set of words, it could be discriminated from speed of processing and memory but not from executive function as measured by tests like the letter-number sequencing test and the Color Trails Test (Siedlecki, Stern, Reuben, Sacco, Elkind & Wright, 2009). Thus, at times, the operational definitions of executive function and cognitive reserve seem to coincide.

A prospective study conducted in France compared onset of cognitive decline as a function of education among individuals aged 65 or older (Amieva et al., 2014). For high-education individuals eventually diagnosed with dementia, the first signs had appeared 15–16 years earlier; for low-education individuals, the first signs appeared 7 years earlier. High education was operationally defined as having at least a primary school certificate; low education was defined as having no education or less than primary school. The interpretation is that high-education individuals can ward off the more devastating consequences of brain pathology for a longer time than can low-education individuals.

Summary and interpretation of education data

Education has a protective effect on cognitive decline and correlates with executive function.

Exercise

Diamond and Lee (2011) review different types of interventions that improve executive function in children. These include, among others, aerobic exercise that involves skill, martial arts training, and mindfulness training. A key helpful feature appears to be consistently increasing the difficulty of the task. Not all executive functions are improved, but several are, and it tends to be the most demanding types of executive function that benefit most. There is also specificity in terms of transfer, depending on the type of intervention. Training in working memory transfers to some working memory tasks but not others and not to other types of executive function. If the intervention is broad, however, such as with developing skill in exercise that requires thought, then transfer to executive function tasks appears to be more general (Best, 2010, 2012). Among typically developing children, those with the worst executive functions gain the most from intervention.

Aerobic exercise alone does not appear to have consistent effects with children or young adults (Guiney & Machado, 2013), but does with old adults. Reviews of the effects of sustained aerobic exercise programs, especially those that combine strength and aerobic training, on adults aged 65 and older in general demonstrate improvement in tasks that measure executive function, such as task-switching and flanker (Bixby, Spalding, Haufler, Deeny, Mahlow, Zimmerman . . . & Hatfield, 2007; Colcombe & Kramer, 2003; Erickson, Miller, Weinstein, Akl & Banducci, 2012). Even a mere 20 min of treadmill exercise at least temporarily improves cognitive function, unlike 20 min of exergaming (where individuals interact with a virtual exercise scene and move their bodies in a simulation of, for example, skiing) or video game playing (O'Leary, Pontifex, Scudder, Brown & Hillman, 2011). Cybercycling – cycling on a stationary bike with simulated visuals – has been compared with equivalent cycling without any visuals in a group of adults averaging age 76 in the cyber group and age 81 in the normal exercise group (Anderson-Hanley, Arciero, Brickman, Nimon, Okuma, Westen, Merz, Pence, Woods, Kramer & Zimmerman, 2012). Both groups improved on tests of executive function over a 3-month period, but the cyber group improved more, suggesting perhaps that simultaneous engagement of more than one cognitive process is beneficial.

A study of over a million Swedish men who were followed for an average of 42 years found that low cardiovascular fitness and low cognitive performance at age 18 were associated with earlier cognitive decline and dementia (Nyberg, Åberg, Schiöler, Nilsson, Wallin, Torén & Kuhn, 2014). The men were conscripts into the Swedish military, thus comprising a good community sample of young men. The study used proportional hazard ratios to estimate the independent and combined effects of cardiovascular fitness and cognitive performance on both the development of cognitive decline and the development of early dementia. Each showed an independent effect and the two together showed an even stronger effect (Nyberg et al., 2014). An obvious benefit of this study is the extraordinary sample size.

Summary and interpretation of exercise data

Some individuals are more likely than others to engage in exercise. Level of education, for example, correlates with exercise. And the likelihood of maintaining an exercise program once initiated may vary according to motivation, education, or cognition. Nevertheless, when individuals are randomly assigned to exercise groups, those engaging in mindful, stimulating exercise appear to perform better on tasks measuring executive function. A striking feature of the interventions is that it is not necessary to have life-long experience in order to show executive function benefits (as noted by Li et al., 2014). Another striking feature is that the benefits extend to domains other than those on which the enriching experience focused. Aerobic exercise appears overall to improve executive function in older adults (Guiney & Machado, 2013) and is correlated with later cognitive decline.

Music training

Musicians show enhanced performance on executive function tasks compared to non-musicians (Amer, Kalender, Hasher, Trehub & Wong, 2013; Bialystok & DePape, 2009; Hanna-Pladdy & MacKay, 2011; Moreno, Bialystok, Barac, Schellenberg, Cepeda & Chau, 2011). Music lessons also enhance IQ (Moreno et al., 2011; Schellenberg, 2005; Schellenberg & Weiss, 2013).

When musical expertise and bilingualism have been compared in the same experiment, both monolingual musicians and bilingual non-musicians show better overall performance on a Simon task, compared to monolingual non-musicians (Bialystok & DePape, 2009). In that experiment, however, there was no calculation of a Simon incongruency effect, only of reaction times on both congruent and incongruent trials. Bilinguals and musicians were faster on both types of trials than monolingual non-musicians. Visual inspection of the relevant figure suggests that there was no incongruency disadvantage for monolinguals other than being slow; they did not appear to have a larger Simon incongruency effect.

More direct evidence of effects of music training comes from an experiment with 4- to 6-year-olds. Twenty days of computerized musical training that emphasized listening skills led to improved performance on a go/no-go executive function task (Moreno et al., 2011), while computerized visual-art training did not. Similarly, six months of individualized piano instruction for older adults showed a trend of improved performance on a test of executive function (Trails test; Bugos, Perlstein, McCrae, Brophy & Bedenbaugh, 2007). As with exercise, what is striking about the reports of music instruction is that there are executive function benefits after very short periods of time. How long the benefits last is unclear.

Summary and interpretation of music training data

Music training is associated with superior performance on executive function tasks and with later cognitive decline, though there has not been much research in this area.

Active video game experience

Action video game players have better perceptual-motor skills than non-video game players (Green, Li & Bavelier, 2010) and perform better on a variety of executive function tasks, including task switching (Green, Sugarman, Medford, Klobusicky & Bavelier, 2012). Although players' superior performance may be due to intrinsic differences between them and non-players, it may also be causally related to experience in playing active video games. (See Bavelier, Green, Pouget & Schrater, 2012, for a review).

An experiment comparing monolingual and bilingual young adults who did or did not play video games found that video game players were faster overall than non-gamers, as one would expect, on two versions of the Simon task, one using squares and the other using arrows (Bialystok, 2006). For both versions, there were blocks of low-switch trials, where switches in the spatial position of the stimulus or the finger required to respond happened seldom, and high-switch trials, where switches happened frequently. For the task using squares, there were no differences as a function of language status or video game experience. Oddly, although high-switch trials were more difficult than low-switch trials, participants were faster on incongruent than congruent high-switch trials, suggesting that the task was not measuring what was intended. On low-switch trials there did appear to be an incongruency effect.

The task with arrows was more complex, because participants had to respond according to the direction the arrow was pointing, whether the arrow itself was on the left or right side. An advantage was reported for bilinguals, but only for high-switch trials. On those high-switch trials, however, there was no effect of congruency, again suggesting the task was not measuring what was intended.

There is some evidence of a training effect: tasks testing cognitive control and flexibility are performed better after 15 hours of training on active video games than after practice on a puzzle (Strobach, Frensch & Schubert, 2012). (For reviews, see Bavelier et al., 2012; Bisoglio, Michaels, Mervis & Ashinoff, 2014.). There have also been failures to see improvement from training (e.g., Boot, Kramer, Simons, Fabiani & Gratton, 2008). The possible relevant differences between successful and unsuccessful training conditions and testing parameters remain unclear (Bisoglio et al., 2014). Older adults can benefit in multi-tasking from some forms of video game training (Anguera, Boccanfuso, Rintoul, Al-Hashimi, Faraji, Janowich, Kong, Larraburo, Rolle, Johnston & Gazzaley, 2013). Whether the benefits are executive function benefits or a wider group of cognitive benefits is not clear.

Summary and interpretation active video game playing data

Active video game players show somewhat inconsistent benefits on executive function tasks and can even show deficits (e.g., Bailey, West & Anderson, 2010, show a deficit for active video game players compared to nonplayers in one condition of a modified version of a Stroop task). Active video game experience also appears to have different effects on different tasks. For switching tasks there are benefits, but for tasks requiring lack of attention to peripheral distractors there are costs. There is no evidence concerning active video game experience and onset of cognitive decline.

Socioeconomic status (SES)

A review of effects of SES on executive function concludes that evidence of a positive effect of higher SES is found even in infancy (Lawson, Hook, Hackman & Farah, in press). Since SES is composed of different factors (e.g., family income, parental education) that themselves correlate with other variables (such as cognitive enrichment in the child's household and engagement in leisure activities like music and sports), and since SES tends to correlate with many predictors of life success, including health, education, and income, it is not surprising that it would also be associated with better executive function. SES is also correlated with later cognitive decline (e.g., Goldbourt, Schnaider-Beeri & Davidson, 2007) but it is difficult to disentangle SES from the other factors it is correlated with.

Summary and interpretation of SES data

SES is probably only a proxy for the relevant challenging activities that lead to better executive function.

Miscellaneous factors

Leisure activities, social activities, and personality variables may promote cognitive reserve. In a prospective probability sample of 1772 non-demented individuals aged 65 and over, followed for up to 7 years, 207 were diagnosed with dementia. Those who engaged in more than six leisure activities showed later onset of dementia, even after controls for education and occupation, than did those who engaged in fewer than six (Scarmeas, Levy, Tang, Manly & Stern, 2001). Leisure activities may overlap to a much lesser extent with executive function than education does, although some may be cognitively demanding.

A study of 1138 non-demented individuals with a mean age of 79 examined the role of involvement in social activities such as volunteering, visiting relatives, and so on to cognitive reserve. Over the 5 years of the study, 224 participants received diagnoses of dementia. Individuals who engaged in more social activities showed slower cognitive decline than those who engaged in fewer. Controls for education, income, personality, engagement in cognitively stimulating activities (such as reading a book), and physical activity did not alter the relation between time spent in social activities and rate of decline (James, Wilson, Barnes & Bennett, 2011). The results were apparently not due to the inclusion of less cognitively fit individuals who were cognitively unable to spend time in social activities. Not all studies, however, see beneficial results for social activities (e.g., Brown, Gibbons, Kennison, Robitaille, Lindwall, Mitchell, Shirk, Atri, Cimino, Benitez, MacDonald, Zelinski, Willis, Schaie, Johansson, Dixon, Mungas, Hofer & Piccinin, 2012).

Personality variables were measured in a prospective community sample; individuals who were low in neuroticism and high in conscientiousness showed higher cognitive functioning in the face of neural damage. Such personality variables may themselves be correlated with other variables that improve cognitive functioning or may be partially dissociable (Terracciano, Iacono, O'Brien, Troncoso, Sutin, Ferrucci, Zonderman & Resnick, 2013).

Summary and interpretation of miscellaneous factors

Leisure and social activities may provide challenges sufficient to delay cognitive impairment, but may also sometimes be a consequence of better cognition. Having an agreeable and conscientious personality may contribute independently to healthy aging or may be a consequence of other variables.

3. Where are we now? Where do we go next?

'Executive function' is a term that covers a large variety of cognitive abilities. The underlying latent variables appear to include two specific factors of updating and shifting and a common factor related to keeping task goals in mind and biasing behavior accordingly (Miyake & Friedman, 2012). I have suggested that that common factor be thought of as inhibition, since it correlates very highly with inhibition. Very few tasks measure only a single component of executive function, and most tasks involve processes outside of as well as within executive function. Different components of executive function may be positively correlated, uncorrelated, or negatively correlated with each other, depending on the task. Even tasks that appear superficially similar, such as the Simon and flanker, tend not to correlate, demonstrating the need for a fine-grained task analysis.

Many experiments examining the contribution of bilingualism or other cognitive experiences to executive function measure the contribution with different tasks, of which those listed in Supplementary Material, Appendix 1 are not exhaustive. Most tasks, like the Simon, can exist in variants, and each variant introduces its own sources of variability. Without a systematic task analysis that elucidates the reasons for the inconsistencies across task variants and across tasks, we will not be able to understand the cognitive mechanisms underlying better or worse performance.

When the effects of bilingualism are compared with the effects of other cognitively enriching activities, we see somewhat inconsistent benefits for all of them. Although I have highlighted the inconsistencies in the bilingualism literature, there are inconsistencies for most variables. That is to be expected if many different activities contribute to enhanced executive function. In all the cases that have been examined, consistent exposure to cognitive challenges leads to better executive function.[5] We have probably only scratched the surface of enriching activities. Further, those activities are at best proxies for the underlying mechanisms. Higher levels of education, for example, tend to be associated with a variety of improved life outcomes. But education is not a mechanism, and may itself be a consequence of other qualities, such as IQ, socioeconomic status, and motivation. Those other qualities are also not mechanisms. An advantage of the bilingualism literature is the consistent search for mechanisms.

The wide variety of factors that lead to improved executive function and later onset of cognitive decline, and the variation in how much experience is necessary to improve executive function, demonstrate the need to rethink what the underlying mechanisms are. Either there is a single, high-level, description of what the disparate activities have in common or there are many different underlying mechanisms that can lead to enhanced executive function. I proposed at the beginning of this paper that we consider multiple underlying mechanisms, befitting the multiple character of executive function, the tasks that measure it, and the experiences that improve executive function and delay cognitive decline. The multiplicity of helpful factors confirms the likelihood that there are many underlying mechanisms.

[5] One exception is the study by Dye et al (2009), where video gamers showed a larger flanker effect, presumably because their attention spread over the whole display to a greater degree than was true for non-players.

Bilingualism's benefits for executive function are especially inconsistent for children and young adults. The strongest and most consistent effects are seen in old people. (That could partially be a function of small numbers of studies. As more and larger studies are completed, a wider variety of findings may be expected.) But the data for the effects of *all* enriching experiences on executive function are inconsistent. Why are advantages inconsistent from experiment to experiment and particularly difficult to demonstrate with children and college-age adults?

My suggestion is that children and young adults engage in many cognitively challenging activities and that those challenges are at least equivalent to the cognitive challenges provided by bilingualism. Further, some of those activities may need relatively little investment of time for relatively short duration (e.g., exercise) in order for benefits to occur, while others may need longer and more intensive experience (e.g., speaking more than one language, Li et al., 2014). Quick-acting benefits may also not last very long if they are not continued.

For experiments in which the participants are college students, college itself provides cognitively challenging activities (or so professors like to think). Middle-aged and old adults have a less varied life; old adults in particular tend to have fewer cognitively enriching experiences than younger adults. One reason for decline in cognitive enrichment in old age may be that brain pathology itself makes experiences that were formerly challenging aversive. Finally, although there may no absolute limit on how much one can improve cognitive function, there may be a point of diminishing returns. Even highly educated people with many cognitive challenges experience cognitive decline and may live long enough to experience dementia.

Where are we so far?

1. Research on the relation between executive function and bilingualism would benefit from comparing and contrasting bilingualism and other factors that influence executive function.
2. Researchers fail to find an advantage for bilingualism in part because there are many other cognitively enriching activities that monolinguals may engage in that are as potent as, or more potent than, bilingualism.
3. Given the diversity of ways that one can improve executive function and can delay cognitive decline, it is likely that there are many underlying mechanisms.

Where do we go next? A host of methodological issues should be resolved. One is whether the field should undertake exact replications, conceptual replications, or both, in order to determine the conditions under which effects are reliably obtained (Paap, 2014; Simons, 2014; Stroebe & Strack, 2014). Others are whether measures or tasks should be standardized (see, e.g., Paap, 2014), whether scores should be standardized to avoid large differences across groups, and whether data analytic procedures should be standardized. See also Pashler and Harris, 2012; Ledgerwood, 2014; and the series of articles on methods published with Ledgerwood, 2014, in *Perspectives in Psychological Science, 9 (3)*, 2014.

Theoretical issues concern executive function, bilingualism, and the relation between them. About executive function: is there actually such a thing as executive function that can justifiably be separated from other cognitive processes? If so, what are the underlying cognitive mechanisms? By understanding what experiences, in what contexts, support superior executive function, and which do not, we can understand the underlying mechanisms. From the perspective of executive function, studying bilingualism effects would be similar to studying effects of any enriching cognitive experience.

About bilingualism: research on bilingualism and executive function proceeded from a clear hypothesis about the underlying mechanism needed to efficiently negotiate having two or more languages, namely, inhibition, since speakers must inhibit the language(s) not in use (Bialystok, 1999). The evidence for inhibition at the cognitive level is weak among children and young adults and is in any event insufficient for explaining some benefits of bilingualism (Kroll & Bialystok, 2013). Another hypothesis, based on the idea that bilinguals must monitor which language is appropriate in a given context, was monitoring (e.g., Costa et al., 2009). It, too, seems incomplete. In the face of cases that specific hypotheses do not handle, some researchers have suggested more global mechanisms, such as mental flexibility (Kroll & Bialystok, 2013).

In the introduction I suggested the opposite approach, namely, investigating many specific mechanisms. A major advantage of the inhibition hypothesis was its specificity. That allowed researchers to determine that it was irrelevant in some circumstances and that tasks apparently measuring inhibition did not show consistent benefits for bilinguals. The fact that a mechanism is incomplete or spotty in its effects does not mean that it never operates, nor that it should be abandoned. Rather, by seeing when and where specific effects occur, it will be possible both to understand the mechanisms that subserve bilinguals' excellent performance with their languages and the consequences of those mechanisms for cognitive processes.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1366728914000522

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