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Interpreting cognitive decline in the face of cognitive reserve

Does bilingualism affect cognitive aging?

Ellen Bialystok,[1] John A. E. Anderson[1] and John G. Grundy[1,2]
[1]Department of Psychology, York University / [2]Department of Psychology, Iowa State University

Evaluation of the cognitive level of older adults, including decisions about meeting clinical thresholds for dementia, is typically based on behavioral levels of performance. However, individuals with high cognitive reserve will outperform the levels typically associated with their brain structure, providing inaccurate assessments of their status. We define cognitive reserve as the relation between brain integrity and cognitive level, and use the case of bilingualism as a source of cognitive reserve to illustrate how information from only one can distort the interpretation of the individual's cognitive status.

Keywords: cognitive reserve, aging, brain integrity

There has been much discussion about the impending worldwide crisis in health care attributable to an aging population and increasing prevalence of dementia (Prince, Comas-Herrera, Knapp, Guerchet, & Karagiannidou, 2016). For this reason, much hope rests on new pharmacological developments to provide treatments and possibly cures for the most severe forms of dementia, notably Alzheimer's disease (AD). However, in a comprehensive review of all current clinical trials for AD, Cummings et al. (2017) conclude that the success of drug development for AD is low and progress is extremely slow. For example, they note that to complete the clinical trials currently in progress, it will be necessary to recruit 54,073 patients, and point out that "trial recruitment is among the slowest and most expensive of all aspects of clinical trial conduct" (p. 380). Moreover, approximately half of the clinical trials in the final stage, Phase III, are aimed at reducing or eliminating amyloid, even though the amyloid hypothesis is still contentious as a causal mechanism of AD. For example, Brayne and Miller (2017) report that less

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than 2% of AD cases are associated with the genetic mutation responsible for the production and metabolism of amyloid.

With little progress in the development of pharmacological interventions for cognitive complaints, attention has increasingly focused on the lifestyle factors that might postpone the appearance or lessen the severity of symptoms, a set of factors called cognitive reserve. According to Cummings et al. (2017), "overall frequency of [Alzheimer's] disease would be decreased by nearly 50% if the onset of the disease could be delayed by 5 years." However, much about cognitive reserve remains unknown. The main gap in knowledge is in understanding the mechanism by which these experiences are able to positively impact cognitive status.

Much of the confusion comes from the interplay between focusing on brain structures responsible for reserve, sometimes called "neural reserve", "brain reserve", or "brain maintenance", and cognitive factors that allow individuals to over-ride or compensate for brain levels, sometimes called "cognitive reserve". Although related, the nature of their interconnection is unclear. Many researchers acknowledge these distinctions but still refer to all these concepts with the umbrella term "cognitive reserve". Barulli and Stern (2013) made an important contribution towards clarifying these questions by providing an overview of the relevant terms, including a Glossary that delineates a unique meaning for each, but the relationships between them remain unspecified. Although establishing clear definitions for the terms is crucial for understanding these issues, the central questions regarding how reserve works and how it can be identified are still unsolved. Therefore, there is a problem in knowing how to interpret cognitive performance in older adults who may be demonstrating cognitive reserve: To what extent can their cognitive level be used to infer the state of brain structure or presence of neuropathology? For this reason, understanding the actual cognitive level and brain integrity of older adults is problematic because evidence from behavior alone is inadequate to make decisions about brain status and possible clinical decline. These relationships become particularly obscure when individuals have passed clinical criteria for dementia.

Defining and identifying cognitive reserve

The idea that experiences can be powerful sources of cognitive preservation was surprising at first. Although it was long known that enriching experience had positive effects on learning in rats (Hebb, 1949), the extension of this capacity to humans, particularly in adulthood, was not fully recognized. However, a transformational change in cognitive neuroscience came from evidence for lifelong experience-related neuroplasticity (Pascual-Leone, Amedi, Fregni, & Merabet,

2005). This evidence opened possibilities for improving human functioning by building cognitive reserve and was instrumental in stimulating widespread research on reserve.

The first evidence for cognitive reserve in older adults came from the findings that post-mortem examination of cognitively normal individuals sometimes revealed brain pathology associated with AD (Katzman et al., 1989). The assumption had been that there was a direct connection between neuropathology and AD symptomology, so the absence of symptoms in these cases was unexpected. As an explanation for these results, Stern (2002) proposed that cognitive reserve allowed those individuals to compensate for AD neuropathology and function at the level of unaffected individuals, a position he subsequently elaborated (Stern, 2012), although even there, he acknowledged that the mechanisms responsible for this reserve were unknown.

The lifestyle factors that contribute to reserve cover a range of experiences, such as physical activity (McAuley, Kramer, & Colcombe, 2004), academic achievement (Stern, Gurland, Tatemichi, Tank Wilder, & Maveaux, 1994), formal education (Tucker-Drob, Johnson, & Jones, 2009), and socioeconomic status (Sattler, Toro, Schonknecht, & Schroder, 2012). Another factor proposed by recent research is bilingualism. The possibility was first suggested in a study by Bialystok, Craik, Klein, and Viswanathan (2004) in which healthy middle-aged and older bilinguals outperformed their monolingual counterparts on an executive function (EF) task. The notion was further supported by evidence from several studies showing the bilinguals were diagnosed with AD at a significantly older age than monolinguals (Alladi et al., 2013; Bialystok, Craik & Freedman, 2007; Woumans et al., 2015). In a review of this research, Bak and Alladi (2014) concluded that "bilingualism has a positive effect on cognition throughout the lifespan" (p. 2). Nonetheless, the claims for the protective effects of bilingualism against dementia in aging remain controversial (e.g., Crane et al., 2010; Mukadam, Jichi, Green, & Livingston, 2018). The question, therefore, is why it is so difficult to obtain decisive evidence in support of the argument that bilingualism leads to cognitive reserve and protects cognitive function and brain structure in older age. The question is important because confirming that cognitive reserve is a consequence of bilingualism changes the way behavioral outcomes from older bilinguals can be interpreted, especially in the absence of brain data.

Our claim is that the problem of establishing the presence of cognitive reserve lies in its definition and the nature of evidence necessary to demonstrate its effects. In the absence of a clear definition of cognitive reserve, the best approach is to use the descriptive interpretation suggested by Barulli and Stern (2013) in which they focus on the mismatch between brain pathology and expected cognitive performance. In these terms, cognitive reserve can be defined as the decoupling

of measures of brain integrity and assessments of cognitive function. The relation between these two in aging is reasonably well understood; there is in general a correlation such that decline in one is calibrated to decline in the other (Fjell & Walhovd, 2010; Raz et al., 2010). In this way, cognitive reserve emerges from the relation between brain level and cognitive level, not from an assessment of either of them alone. Therefore, studies that report levels of brain integrity or cognitive level without the other measure and in the absence of a relevant control cannot be interpreted unambiguously.

This approach of examining the *relation* between brain level and cognitive level raises several methodological problems. The first is to determine the appropriate reference group or control group for each measure. If the intention is to investigate whether a particular experience, bilingualism, confers cognitive reserve in older adults relative to comparable monolinguals, then should monolinguals and bilinguals be matched on brain integrity, cognitive level, both, or neither? A second is to establish the precise measure of brain integrity or cognitive outcome that is most relevant. For example, hippocampal atrophy accompanied by intact memory would signal cognitive reserve, but what about other brain and cognitive measures in the same individual – should they also be altered to indicate cognitive reserve or is it sufficient to demonstrate anomalous performance in a single domain? Clearly, the determination of whether cognitive reserve is detected will depend on these decisions.

Does bilingualism confer cognitive reserve?

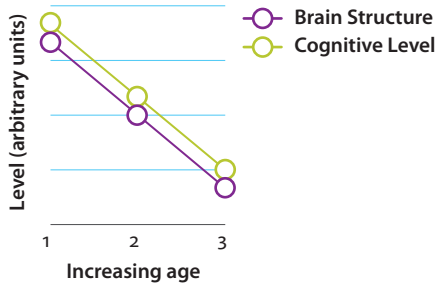
Evidence for the effect of bilingualism on cognitive reserve is inconsistent: Some studies of older adults show better performance by bilinguals than monolinguals on executive control tasks (Soveri, Rodriguez-Fornells, & Laine, 2011) and others show no difference (Antón, Fernandez Garcia, Carreiras, & Dunabeitia, 2016); some patient studies show later onset of symptoms of dementia for bilinguals than monolinguals (Bialystok, Craik, & Freedman, 2007) and others show no difference (Lawton, Gasquoine, & Weimer, 2015); and incidence studies of dementia generally show no statistical difference between the two language groups (Zahodne, Schofield, Farrell, Stern, & Manly, 2014) although a population study based on national levels of bilingualism showed a significantly lower incidence in more bilingual countries (Klein, Christie, & Parkvall, 2016; for review see Calvo, Garcia, Manoiloff, & Ibanez, 2016). Our suggestion is that one reason for the inconsistency is that the studies differed on how participants were selected and how matching was applied. As we explained above, cognitive reserve is found in

the *relation* between brain and behavior, not in either one alone, so the matching process is crucial.

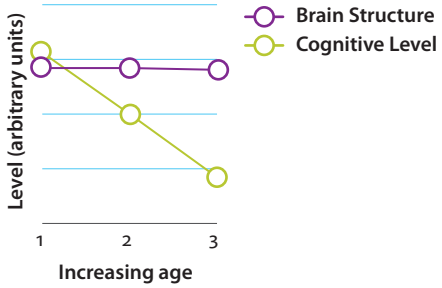
It is not controversial to claim that there are interactions between brain and behavior and that both should be considered in attempts to understand cognitive ability in older adults. With healthy aging, brain atrophy and cognitive decline are continuous processes and clearly interact. However, because these relationships are predictable, it is generally possible to compare individuals for either brain or behavioral measures to answer specific questions without necessarily requiring details from both; thus, one can compare performance differences between 60-year-olds and 80-year-olds, between men and women, or between individuals in happy and sad affective states. With cognitive reserve, these relationships become unpredictable, so estimates of cognitive level or brain integrity require information from both.

Relation between age, brain structure and cognitive level

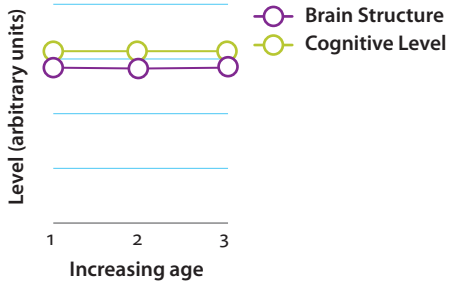
Figure 1 illustrates five trajectories for how brain structure and cognitive level can vary with aging. In Panel A, both cognitive level and brain structure decline with age, the typical pattern observed in the population. Panel B illustrates a case in which there is typical cognitive decline but no evidence of an age-related decline in the neural substrate being examined. Such a case might arise when a group comparison of a neural substrate does not yield a difference in a specific region, for example the occipital lobe, but cognitive performance continues to decline at equal rates for both groups. Such a finding would indicate that (a) the lack of group difference in neural tissue may be spurious, or more likely (b) there is a mismatch between the cognitive task and the neural substrate such that they do not map cleanly onto one another. Panels C and D represent cases where older individuals manage to resist decline or maintain levels in the neural substrate (or, as depicted in Panel D, even start to reverse age effects) and this in turn yields concomitant gains in cognitive performance relative to age-matched peers. Finally, Panel E shows the classic "cognitive reserve" pattern described by Stern (2002). In cases attributed to cognitive reserve, it may also be that cognition is re-routed through other neural substrates that are maintained or boosted by life activities. Thus, these terms are not mutually exclusive and depend on which anatomical, cognitive, or reserve factors are the focus of attention.



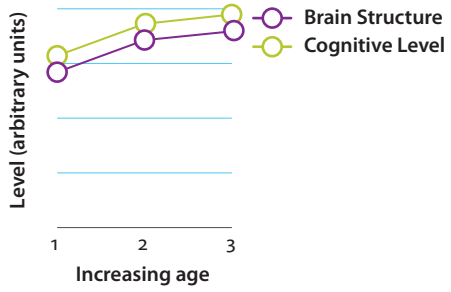
a. Typical Aging I shows a decline in both brain structure and cognitive level (in arbitrary units) with increasing age



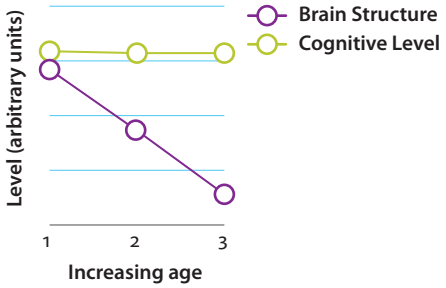
b. Typical Aging II represents normal cognitive decline with an intact brain measure suggesting that perhaps a different neural measure should be implicated



c. Neural/Brain Reserve I shows a pattern where individuals *maintain* both brain structure and cognitive level with increasing age



d. Neural/Brain Reserve II represents a pattern where individuals *increase* brain structure and cognitive levels above what would be expected after controlling for age



e. Cognitive reserve represents a pattern of cognitive maintenance in conjunction with brain atrophy

Figure 1. Five trajectories of aging

Determining cognitive reserve from behavioral data

A substantial body of research in cognitive aging examines changes in performance over time based only on behavioral data. In an influential study, Park and colleagues (Park et al., 2002) tested 345 healthy individuals between the ages of 20 and around 90 years old on a large battery of cognitive tasks. The results documented the declining ability in the domains tested over this period based on the behavioral measures. A summary of the results in a later review paper by Park and Reuter-Lorenz (2009) provides a comprehensive description of cognitive change over this period. The original study and the review paper provide an important benchmark that can be used to evaluate cognitive reserve by comparing high or low reserve groups against this standard. However, the cognitive data are not accompanied by brain data, limiting the use of the data base for the purpose of identifying factors that lead to cognitive reserve. Put another way, the question of whether a particular group demonstrates cognitive reserve could be approached by comparing performance of the group to the standards reported in the study by Park et al. (2002), but a decision about whether the results actually reflect reserve could not be made without accompanying brain data.

The type of behavioral data available in research on cognitive reserve varies greatly, contributing to the difficulty of comparing results across studies. In studies that include experimental tasks, they are likely to be executive function (EF) tasks such as Stroop, flanker, Simon, and the like (e.g., Salvatierra & Rosselli, 2010). Other studies include neuropsychological assessments, sometimes alone and sometimes in conjunction with EF tasks. Therefore, it is useful to discuss the quantity and quality of behavioral data available for matching groups to determine the presence of reserve. In some studies, a single behavioral measure (e.g., MMSE)

is used to ascertain the equality of cognitive level between groups, whereas in other studies, groups are compared on 15 or more behavioral outcome measures. This *continuum of granularity* in behavioral matching contributes to the strength of the relationship between the behavioral evidence and the conclusions regarding the presence of cognitive reserve.

Several studies have examined differences between monolinguals and bilinguals performing EF tasks and made claims about reserve exclusively on the basis of behavioral data. Antón, Fernandez Garcia, Carreiras, & Dunabeitia (2016) tested 48 elderly monolinguals and bilinguals from Basque on a verbal and nonverbal version of the Stroop task. The groups were comparable in age, education, MMSE, and general IQ measured by an abridged version of the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 1990). The authors found the groups performed equivalently on the Stroop task and concluded that bilingualism does not contribute to cognitive reserve in the elderly. However, without corresponding brain data, especially for older adults, behavioral data are ambiguous. Specifically, brain data could reveal whether the performance level reported for bilinguals that was comparable to that of monolinguals was achieved in spite of measurable brain decline or early presence of neuropathology in bilinguals. In this case, the implication is that if monolinguals were to have been matched on brain status, their cognitive performance would be lower. Because no brain data were available, no conclusions about cognitive reserve can be drawn from these null findings.

A different approach to using behavioral data in studying cognitive level in older adults was implemented in a study conducted in Scotland by Bak and colleagues (Bak et al., 2014). Participants were tested on a variety of cognitive and IQ measures more than 60 years after having been assessed for childhood intelligence in 1947. Because IQ score is considered to be a reliable measure, the expectation was that there would be a strong positive relation between IQ at 11 and IQ at 73. There were 853 participants, all of whom were monolingual speakers of English as children, but over the course of their lives, many had become bilingual. Analyses of the relation between childhood and adult IQ after controlling for various background variables showed that monolinguals and "passive" bilinguals displayed the predicted linear relationship between the two IQ scores but "active" bilinguals outperformed their childhood IQ when tested as older adults. This was particularly the case for those with the lowest IQ percentile in the initial test, suggesting that reserve factors such as bilingualism have their greatest impact for individuals who are disadvantaged. This pattern is consistent with studies showing greater advantages of bilingualism for individuals with low SES and low education than for their higher SES and more educated peers (Alladi et al., 2013; Gollan et al., 2011). The pattern in the Bak et al. (2014) study is opposite to the typical one in which scores decline with age in that the IQ scores for the bilinguals increased

over their expected values. But what mechanism would lead to an improvement in cognitive level? Presumably increases in cognitive level are also an index of reserve, but again without brain data, it is difficult to know how to interpret them.

A large-scale study of older adults in Switzerland provides compelling evidence for a protective effect of bilingualism on cognition using only behavioral data. Ihle, Oirs, Fagot, and Kliegel (2016) examined 2,812 older adults from Switzerland and showed that number of languages spoken significantly predicted processing speed and verbal ability over and above leisure activities, physical demands of their jobs, and gainful activity, but not education or cognitive demand of the first job. This finding is consistent with the above data suggesting that the role of bilingualism can help to boost cognition when other lifestyle factors such as work and education are lacking. Similarly, Kave, Eyal, Shorek, and Cohen-Mansfield (2008) measured outcomes on two cognitive screening tasks on 814 older adults over a period of 12 years. As in the study by Ihle et al. (2016), the number of languages spoken significantly predicted cognitive score; a greater number of languages was associated with less decline. In both cases, higher levels of multilingualism were related to greater preservation of cognitive function on behavioral tests. However, in both cases there were no brain data and no control group. Therefore, several questions remain unanswered. For example, does bilingualism improve or protect cognition despite brain atrophy? Or does bilingualism selectively strengthen other brain structures and allow one to stave off symptoms of decline for longer? These are questions that cannot be answered unless both behavioral and brain data are available.

Evidence for reserve from brain data

Studies of cognitive reserve based on brain data inevitably include some form of cognitive measure. Therefore, unlike the situation with behavioral data, there are no pure cases in which monolingual and bilingual older adults are compared for brain status in the complete absence of some information of functional cognitive level, even though these measures vary greatly across studies. In general, studies with a greater breadth of cognitive measures can make stronger claims about reserve than can studies with fewer, blunter instruments.

This situation can be illustrated by considering two studies by Abutalebi and colleagues who examined the neuroprotective effects of bilingualism. In two consecutive articles, they reported structural differences between groups and argued that they were the basis for reserve in bilinguals. In the first paper, Abutalebi et al. (2014) showed that bilingualism protected the left anterior temporal lobe (L-ATL) from the effects of aging, and in the next study, Abutalebi et al. (2015)

extended these results to show similar effects for the parietal lobe. In both studies, participants were matched on age, education, and SES, but MMSE was the only measure of cognitive status. Monolinguals, but not bilinguals, had a significant negative relationship between L-ATL volume and age, though the correlation values did not significantly differ between groups. Furthermore, picture naming in the second language, a reflection of degree of bilingualism, was positively correlated with L-ATL volume in bilinguals. The conclusion would appear to be that bilingualism is a factor leading to superior aging, or at least a decoupling of aging from neurodegeneration in this region. But is there enough evidence to support that conclusion?

If reserve is defined in terms of the relation between cognitive and brain status, as shown in Figure 1, then these studies do not provide sufficient evidence to evaluate that relation. There are independent reasons that brain status or cognitive status could vary, but unless those changes are linked to each other, the reasons could be independent and irrelevant to reserve. With only MMSE as a cognitive index, the groups may have differed in important ways not captured by the analyses. Essentially, MMSE functions as a screening for threshold levels of dementia, but it is not a sufficiently precise measure of cognitive performance in healthy aging. It is easy for older adults to perform at ceiling on this assessment if they are in good cognitive health, so for healthy older adults, there is little variance is scores. Therefore, the study effectively reports brain data but without meaningful cognitive data.

What interpretations follow from this situation? As the authors point out, learning a second language strengthens the L-ATL and decouples its rate of decline from age (although note that the difference in correlations for the two groups was not significant, weakening this conclusion). This alone is a potential basis for reserve but a connection would need to be made between this region and cognitive level. The L-ATL is primarily associated with semantic memory, although even this connection is controversial (Bonner & Price, 2013), so it may be that use of two languages strengthens brain systems involved in semantic memory. Although such a relation would be important evidence for experience-dependent plasticity, it is not *prima facie* evidence for cognitive reserve. That question can only be addressed with adequate cognitive data.

The Abutalebi et al. studies set up intriguing possibilities for investigating cognitive reserve if adequate cognitive data had been provided. If the L-ATL were relevant for cognitive level, then bilinguals should outperform monolinguals on cognitive tasks, strengthening the original conclusion (consistent with Figure 1, Neural/Brain Reserve I or II). The MMSE is unable to detect these relationships and it is not surprising that the groups were equivalent on this measure. However, in the absence of a relationship between cognitive status and integrity of this

region, there would be no grounds for conclusions regarding cognitive reserve. Instead, the data would show that varying degrees of grey matter volume in the L-ATL had no bearing on cognitive performance regardless of its relationship with bilingualism and aging (as represented by Figure 1, Typical Aging II). In summary, in the absence of cognitive data to contextualize the brain volume results, no clear conclusions about cognitive reserve can be made.

Combining brain and behavioral data

Several studies have had access to data from both brain status and cognitive level, leading to more convincing conclusions about cognitive reserve. To this end, studies that include evidence for functional activation of brain networks, even in the absence of structural measures, support the need to consider brain function as well as behavioral performance. A study by Luk, Anderson, Craik, Grady, & Bialystok (2010) with young adults performing a flanker task and another study by Ansaldo, Ghazi-Saidi, & Adrover-Roig (2015) with older adults performing a Simon task both showed equivalent behavioral performance by monolingual and bilingual participants but different functional activation. In general, the bilinguals used more posterior regions to achieve the same level of performance, demonstrating more efficient use of brain resources that could potentially lead to reserve (for discussion, see Grundy, Anderson, & Bialystok, 2017).

Using both structural and behavioral measures in patients, Duncan et al. (2018) found different levels of cortical thickness in monolingual and bilingual patients with mild cognitive impairment and Alzheimer's disease and different relations between cortical thickness and memory performance in each group. Thus, not only were both types of measures necessary to document differences between monolingual and bilingual patients but also the specific nature of the relation changed as a function of disease severity. These results underline the importance of including both types of measures in assessments of cognitive status.

A study by Gold and colleagues (Gold et al., 2013) investigated white matter integrity in older monolingual and bilingual adults. They matched participants on 13 demographic and neuropsychological variables and additionally reported a measure of executive function, task-switching RTs and accuracy. The results showed that bilinguals had lower values for fractional anisotropy (FA) than monolinguals in a swath of regions including the inferior longitudinal fasciculus, the inferior fronto-occipital fasciculus and the corpus callosum, indicating poorer white matter microstructure. Nonetheless, participants in both groups had similar IQ, working memory, and vocabulary scores, but bilinguals were selectively faster (but not more accurate) on the task-switching EF measure. This careful design

allows a stronger inference of reserve. Despite having less intact white matter in several regions connecting the occipital and temporal lobes to the frontal lobes and the two hemispheres of the frontal lobes to each other, bilinguals still performed as well as monolinguals and, in some cases, exceeded the performance of monolinguals. While it is still possible that the authors failed to capture the specific aspect of cognition reflected by the decline in white matter, that likelihood is low given the extensive neuropsychological battery, increasing confidence in the conclusions.

A clearer criterion for assessing the presence of reserve is available in cases where a clinical diagnosis is available. Patients in each language group can be matched on the severity of their symptoms, so differences in brain metabolism or structure given similar functional progression of the disease allows for interpretations of cognitive reserve (cf. Stern, 2002). Several studies have used this design. Studies examining brain metabolism with Fluoro-deoxy-glucose PET imaging (FDG-PET) have yielded promising results. Low brain metabolic activity, particularly in temporal and parietal regions, are strongly associated with Alzheimer's dementia (Mosconi, 2013). Two studies have compared brain metabolism in older adult bilinguals and monolinguals matched for dementia load, and in both cases, glucose hypometabolism was the proxy for disease severity. Both studies produced consistent results. The first by Kowoll et al. (2016) showed that relative to monolinguals of equal dementia status, bilinguals had reduced metabolism in frontal, temporal, and parietal regions; these are among the first regions affected by Alzheimer's disease. This finding was replicated with a larger, more homogenous dementia sample in a study a year later Perani et al. (2017). Thus, bilingual brains with dementia consume glucose at rates consistent with more advanced disease. Similar results were reported by Schweizer et al. (2012) who compared CT scans from 20 bilinguals and 20 monolinguals with probable dementia. Patients were matched on dementia progression, age, and education, and the outcome variables of interest were the radial width of the temporal horn and the temporal horn ratio, both proxy measures for temporal lobe atrophy. Similar to the results of the metabolism studies, bilinguals with dementia had greater atrophy in temporal lobe regions than monolinguals with identical diseases progression.

Interestingly, reserve can be seen not only in studies of aging and dementia, but also in other neurodegenerative disorders. A recent study examining temporal lobe epilepsy in monolingual and bilingual patients compared to healthy controls demonstrated how bilingualism might protect from neural degeneration in older age. Reyes et al. (2018) had participants complete the Delis-Kaplan Executive Function System Color-Word Inhibition/Switching task as well as the Trail-Making Test-B (TMT-B) to examine EF, while also measuring white matter microstructural integrity using diffusion tensor imaging (DTI). Results revealed that

monolinguals performed more poorly on the TMT-B task than healthy controls, whereas bilinguals did not differ from healthy controls on either EF task. Even more impressively, bilinguals had poorer measures of FA than monolinguals and healthy controls in the cingulum and uncinate fasciculus. Thus, despite deteriorating brains, bilinguals performed equivalently to healthy controls on measures of executive functions. While not an aging study, these findings suggest that bilingualism provides protection against cognitive decline in face of a deteriorating brain.

Similar findings were reported by Alladi et al. (2016) in their examination of the effect of bilingualism on cognitive outcomes following stroke. This study was conducted in Hyderabad India where a high proportion of the population speaks a second language, immigration is low, and education level is mixed. This allows for an examination of the effects of bilingualism without potentially confounding variables, such as group differences in education level or immigration history. The authors tested two possible theories about the relation between stroke and bilingualism. First, they examined whether bilinguals experienced strokes *later* than monolinguals; if this were the case, it would suggest that bilingualism was associated with differences in vascular risk. This outcome was not supported, and on average bilinguals and monolinguals experienced stroke at similar ages. The second theory examined whether bilinguals and monolinguals differed in cognitive recovery following stroke. The results showed that bilinguals were more than twice as likely as monolinguals to regain cognitive levels found prior to the stroke. The authors interpret this finding as being consistent with evidence that bilingualism affords cognitive reserve.

What is clear from these studies is that speaking more than one language allows individuals cope with greater neural insult than monolinguals seem able to withstand, but how does this bear on the actual appearance and diagnosis of dementia?

Retrospective and prospective studies of dementia

Studies of the onset of dementia potentially provide direct evidence for the presence of cognitive reserve. A clinical diagnosis specifies the point at which cognitive function has crossed a threshold and can no longer be considered healthy. Information about the brain, cognitive, social, and contextual factors involved in that diagnosis can provide powerful evidence for the possible presence of cognitive reserve.

Following from Stern's (2002, 2012) explanation of cognitive reserve, individuals with higher levels of reserve should show symptoms later than those with

lower levels of reserve because they were able to compensate for the decline in brain structure as neuropathology progressed. Therefore, if bilingualism confers cognitive reserve, then bilinguals should show symptoms of dementia at an older age on average (and therefore later in the progression of pathology) than monolinguals. This finding has been reported in a number of retrospective studies of disease onset that have controlled for a variety of factors, with the average delay in diagnosis for bilinguals being about 3.5 to 4 years (Bialystok et al., 2007; Craik et al., 2010; Alladi et al., 2013; Woumans et al., 2015; Chertkow et al., 2010).

Retrospective studies provide only approximate data on clinical onset but the advantage is that data can be assembled for large samples relatively easily by using clinical records. Incidence studies, in contrast, provide a more accurate snapshot because they follow a healthy cohort over time and measure changes in relevant variables until a clinical threshold has been passed. For this reason, some investigators believe that incidence data are more valid than retrospective data. However, incidence studies can lack power if the experience under scrutiny is not well represented in the sample being examined. For example, Zahodne et al. (2014) followed a cohort of 1,067 older adults for a period of up to 23 years to document the factors that increased the risk or protected them from the onset of dementia. In the studied cohort, 282 individuals developed dementia. There was no difference in the incidence rate of dementia for monolingual and bilingual adults in the cohort, but bilingualism was associated with better performance on cognitive measures, particularly those assessing executive function. Furthermore, speaking a second language "very well" was associated with a 14% lower risk of converting to dementia than for those who spoke a second language "not at all well". This lowered risk is similar to the significant protective effect of gender (9% reduction over 20 years for women compared to men). The difference between these two effects is that there were 333 men and 734 women, and 47 bilinguals (not including individuals who were less fluent in English) compared to 637 monolinguals, creating an issue of power.

A similar lack of power for a prospective analysis of bilingualism comes from, a study by Ljungberg et al. (2016). The authors followed a cohort of 818 older adults for 10 years, of whom 82 were bilingual. From this group, 112 participants developed dementia, including 102 monolinguals (about 14%) and 10 bilinguals (about 12%), rates that were not significantly different from each other. However, with so few bilinguals, the statistical analysis is inconclusive. These examples illustrate some of the difficulties in obtaining statistical significance in samples that have substantially different representations from each group.

One incidence study that does not suffer from the power issues of the aforementioned studies is a study by Klein, Christie, and Parkvall (2016). The authors examined population-wide levels of Alzheimer's incidence in 93 countries

weighting results by country population, life expectancy, and other relevant variables. Countries were classified as being essentially monolingual or essentially bilingual, with a few countries being multilingual. The results showed that countries in which the population in general spoke at least two languages had a significantly lower rate of AD incidence than monolingual countries, but only in cases where life expectancy was high enough for individuals to be impacted by the disease. This is powerful evidence for the role of bilingualism in boosting population health in an impactful way.

Another problem with incidence studies is that the relevant variable is usually a binary decision about whether or not an individual was diagnosed with the condition. This criterion is problematic: there is no theoretical or empirical reason to believe that bilinguals will not succumb to dementia, so there is no reason to expect that over a long period, the incidence for monolinguals and bilinguals will be different. However, as demonstrated by retrospective studies, bilinguals on average are diagnosed several years later than monolinguals, indicating that they have functioned for some time in spite of the disease. As Cummings et al. (2017) point out, a delay in diagnosis can have profound consequences for individuals and public health, as well as the overall incidence of dementia. Instead, retrospective studies suggest that everyone accrues pathology at similar rates, but that individuals with reserve can withstand this for longer before showing behavioral symptoms. Importantly, incidence studies rarely document the age at which dementia is diagnosed, but when they do, they replicate the finding from retrospective studies that this age is older in bilinguals than in monolinguals (Wilson et al., 2015).

Ideally, an incidence study of bilingualism or other reserve factor would start with two groups matched in every respect other than the reserve factor and these individuals would be followed over a long period of time. Ideally, cognitive and brain measures would be examined to determine whether specific lifestyle factors had conferred reserve. Such a study has in fact been conducted, although not with bilinguals. The Nun Study (Snowdon, 2003) was a longitudinal study of aging and Alzheimer's disease that followed 678 American nuns, 95% of whom agreed to donate their brains to science. To Snowdon's surprise, 12% of the nuns whose brains contained the most severe Alzheimer's pathology (Braak stage 5 and 6) did not receive a diagnosis of dementia in life. This finding spawned the field of cognitive reserve in an effort to identify factors that are protective over the lifespan and allow people to cope with dementia pathology with minimal or no symptoms. Unfortunately, bilingual nuns willing to sign their brains away to science were in short supply, but the study provides a model for how potential reserve factors can be investigated in ways that lead to clear conclusions.

Conclusion

Assessments of cognitive level in older adults are an important aspect of the protocol for monitoring the health of the aging population. As long as individuals function at a sufficiently high level of cognitive ability, and in particular are able to perform the activities of daily living that are a central part of the diagnosis for dementia, they are able to live independently. Independent living adds quality of life to the older adult and to their family and minimizes stress and financial burden on health care systems, including hospitals, nursing homes, and assisted living facilities. These decisions about cognitive status are made primarily on the basis of behavioral evidence, so it is important that reliable measures of cognition are available. However, if the individual is protected by high cognitive reserve, then cognitive level may not be a reliable indicator of brain status. As such, the cognitive level of high reserve older adults may conceal advanced neuropathology that may require attention even though behaviorally the individual functions at a cognitive level comparable to those with low reserve. Therefore, conclusions that the two groups are cognitively equivalent are not warranted, particularly in terms of the expectations for progression of cognitive decline. Stern, Albert, Tang, & Tsai (1999) noted that high reserve individuals decline more precipitously than low reserve individuals once a critical threshold has been crossed. Cognitive measures alone cannot predict this decline, so individuals are unprepared for the rapid deterioration in cognitive level. Similarly, brain measures alone would pathologize a high reserve individual who displayed clinical levels of neural degeneration but functioned cognitively at normal levels. Because cognitive reserve changes the *relation* between brain status and cognitive level, any interpretation of cognition in older adulthood requires both.

There has been much controversy about whether bilingualism has a positive effect on cognitive behavior. Typically, the discussion has centered on conflicting results from behavioral studies with monolingual and bilingual older adults. However, in the absence of brain data to verify the presence of reserve, those behavioral results cannot be interpreted. Future research that attempts to evaluate the effect of experience on cognitive status needs to consider the evidence from brain and cognition and the relation between them to make meaningful conclusions.

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References

Abutalebi, J., Canini, M., Della Rosa, P. A., Green, D. W., & Weekes, B. S. (2015). The neuroprotective effects of bilingualism upon the inferior parietal lobule: A structural neuroimaging study in aging Chinese bilinguals. *Journal of Neurolinguistics*, 33, 3–13. https://doi.org/10.1016/j.jneuroling.2014.09.008

Abutalebi, J., Canini, M., Rosa, P. A. D., Sheung, L. P., Green, D. W., & Weekes, B. S. (2014). Bilingualism protects anterior temporal lobe integrity in aging. *Neurobiology of Aging*, 35, 2126–2133. https://doi.org/10.1016/j.neurobiolaging.2014.03.010

Alladi, S., Bak, T. H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A. K., … & Kaul, S. (2013). Bilingualism delays age at onset of dementia, independent of education and immigration status. *Neurology*, 81, 1938–1944.

Alladi, S., Bak, T. H., Mekala, S., Rajan, A., Chaudhuri, J. R., Mioshi, E., … & Kaul, S. (2016). Impact of bilingualism on cognitive outcome after stroke. *Stroke*, 47, 258–261. https://doi.org/10.1161/STROKEAHA.115.010418

Ansaldo, A. I., Ghazi-Saidi, L., & Adrover-Roig, D. (2015). Interference control in elderly bilinguals: Appearances can be misleading. *Journal of Clinical Experimental Neuropsychology*, 37(5), 455–470. https://doi.org/10.1080/13803395.2014.990359

Antón, E., Fernández García, Y., Carreiras, M., & Duñabeitia, J. A. (2016). Does bilingualism shape inhibitory control in the elderly? *Journal of Memory and Language*, 90, 147–160. https://doi.org/10.1016/j.jml.2016.04.007

Bak, T. H., & Alladi, S. (2014). Can being bilingual affect the onset of dementia? *Future Neurology*, 9, 101–103.

Bak, T. H., Nissan, J. J., Allerhand, M. M., & Deary, I. J. (2014). Does bilingualism influence cognitive aging? *Annals of Neurology*, 75, 959–963.

Barulli, D., & Stern, Y. (2013). Efficiency, capacity, compensation, maintenance, plasticity: emerging concepts in cognitive reserve. *Trends in Cognitive Sciences*, 17, 502–509.

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: Evidence from the Simon Task. *Psychology and Aging*, 19, 290–303.

Bialystok, E., Craik, F. I. M., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia*, 45, 459–464. https://doi.org/10.1016/j.neuropsychologia.2006.10.009

Bonner, M. F., & Price, A. R. (2013). Where is the anterior temporal lobe and what does it do? *Journal of Neuroscience*, 33, 4213–4215. https://doi.org/10.1523/JNEUROSCI.0041-13.2013

Brayne, C., & Miller, B. (2017). Dementia and aging populations–A global priority for contextualized research and health policy. *PLoS Medicine*, 14, e1002275. https://doi.org/10.1371/journal.pmed.1002275

Calvo, N., Garcia, A. M., Manoiloff, L., & Ibanez, A. (2016). Bilingualism and cognitive reserve: A critical overview and a plea for methodological innovations. *Frontiers in Aging Neuroscience*, 7, 249. https://doi.org/10.3389/fnagi.2015.00249

Chertkow, H., Whitehead, V., Phillips, N., Wolfson, C., Atherton, J., & Bergman, H. (2010). Multilingualism (but not always bilingualism) delays the onset of Alzheimer disease: evidence from a bilingual community. *Alzheimer Disease & Associated Disorders*, 24, 118–125.

Cummings, J., Lee, G., Mortsdorf, T., Ritter, A., & Zhong, K. (2017). Alzheimer's disease drug development pipeline: 2017. *Alzheimer's & Dementia*, 3, 367–384. https://doi.org/10.1016/j.trci.2017.05.002

Craik, F. I., Bialystok, E., & Freedman, M. (2010). Delaying the onset of Alzheimer disease Bilingualism as a form of cognitive reserve. *Neurology*, 75, 1726–1729.

Crane, P. K., Gruhl, J. C., Erosheva, E. A., Gibbons, L. E., McCurry, S. M., Rhoads, K., … & White, L. (2010). Use of spoken and written Japanese did not protect Japanese-American men from cognitive decline in late life. *Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 65, 654–666.

Duncan, H. D., Nikelski, J., Pilon, R., Steffener, J., Chertkow, H., & Phillips, N. A. (2018). Structural brain differences between monolingual and multilingual patients with mild cognitive impairment and Alzheimer disease: Evidence for cognitive reserve. *Neuropsychologia*, 109, 270–282. https://doi.org/10.1016/j.neuropsychologia.2017.12.036

Fjell, A. M., & Walhovd, K. B. (2010). Structural brain changes in aging: courses, causes and cognitive consequences. *Reviews in the Neurosciences*, 21, 187–222.

Gold, B. T., Kim, C., Johnson, N. F., Kryscio, R. J., & Smith, C. D. (2013). Lifelong bilingualism maintains neural efficiency for cognitive control in aging. *Journal of Neuroscience*, 33, 387–396.

Gollan, T. H., Salmon, D. P., Montoya, R. I., & Galasko, D. R. (2011). Degree of bilingualism predicts age of diagnosis of Alzheimer's disease in low-education but not in highly educated Hispanics. *Neuropsychologia*, 49, 3826–3830.

Grundy, J. G., Anderson, J. A. E., & Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences*, 1396(1), 183–201. https://doi.org/10.1111/nyas.13333

Hebb, D. O. (1949). *The Organization of Behavior*. New York: Wiley.

Ihle, A., Oris, M., Fagot, D., & Kliegel, M. (2016). The relation of the number of languages spoken to performance in different cognitive abilities in old age. *Journal of Clinical and Experimental Neuropsychology*, 38, 1103–1114.

Katzman, R., Aronson, M., Fuld, P., Kawas, C., Brown, T., Morgenstern, H., … & Ooi, W. L. (1989). Development of dementing illnesses in an 80–year–old volunteer cohort. *Annals of Neurology*, 25, 317–324.

Kaufman, A. S., & Kaufman, N. L. (1990). *Manual for the Kaufman brief intelligence test*. Circle Pines, MN: American Guidance Service.

Kave, G., Eyal, N., Shorek, A., & Cohen-Mansfield, J. (2008). Multilingualism and cognitive state in the oldest old. *Psychology and Aging*, 23, 70–78.

Klein, R. M., Christie, J., & Parkvall, M. (2016). Does multilingualism affect the incidence of Alzheimer's disease? A worldwide analysis by country. *SSM – Population Health*, 2, 463–467. https://doi.org/10.1016/j.ssmph.2016.06.002

Kowoll, M. E., Degen, C., Gorenc, L., Küntzelmann, A., Fellhauer, I., Giesel, F., … & Schröder, J. (2016). Bilingualism as a contributor to cognitive reserve? Evidence from cerebral glucose metabolism in mild cognitive impairment and Alzheimer's disease. *Frontiers in Psychiatry*, 7, 62.

Lawton, D. M., Gasquoine, P. G., & Weimer, A. A. (2015). Age of dementia diagnosis in community dwelling bilingual and monolingual Hispanic Americans. *Cortex*, 66, 141–145. https://doi.org/10.1016/j.cortex.2014.11.017

Ljungberg, J. K., Hansson, P., Adolfsson, R., & Nilsson, L. G. (2016). The effect of language skills on dementia in a Swedish longitudinal cohort. *Linguistic Approaches to Bilingualism*, 6, 190–204.

Luk, G., Anderson, J. A. E., Craik, F. I. M., Grady, C., & Bialystok, E. (2010). Distinct neural correlates for two types of inhibition in bilinguals: Response inhibition and interference suppression. *Brain and Cognition*, 74, 347–357.

McAuley, E., Kramer, A. F., & Colcombe, S. J. (2004). Cardiovascular fitness and neurocognitive function in older adults: A brief review. *Brain, Behavior, and Immunity*, 18, 214–220.

Mosconi, L. (2013). Glucose metabolism in normal aging and Alzheimer's disease: methodological and physiological considerations for PET studies. *Clinical and Translational Imaging*, 1, 217–233.

Mukadam, N., Jichi, F., Green, D., & Livingston, G. (2018). The relationship of bilingualism to cognitive decline: The Australian Longitudinal Study of Ageing. *International Journal of Geriatric Psychiatry*, 33, e249–e256.

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging*, 17, 299–320. https://doi.org/10.1037/0882-7974.17.2.299

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology*, 60, 173–196.

Pascual-Leone, A., Amedi, A., Fregni, F., & Merabet, L. B. (2005). The plastic human brain cortex. *Annual Review of Neuroscience*, 28, 377–401.

Perani, D., Farsad, M., Ballarini, T., Lubian, F., Malpetti, M., Fracchetti, A., … & Abutalebi, J. (2017). The impact of bilingualism on brain reserve and metabolic connectivity in Alzheimer's dementia. *Proceedings of the National Academy of Sciences*, 114, 1690–1695.

Prince, M., Comas-Herrera, A., Knapp, M., Guerchet, M., & Karagiannidou, M. (2016). *World Alzheimer Report 2016: Improving healthcare for people living with dementia*. London: Alzheimer's Disease International.

Raz, N., Ghisletta, P., Rodrigue, K. M., Kennedy, K. M., & Lindenberger, U. (2010). Trajectories of brain aging in middle-aged and older adults: regional and individual differences. *NeuroImage*, 51, 501–511.

Reyes, A., Paul, B. M., Marshall, A., Chang, Y. H. A., Bahrami, N., Kansal, L., … & McDonald, C. R. (2018). Does bilingualism increase brain or cognitive reserve in patients with temporal lobe epilepsy? *Epilepsia*, 59, 1037–1047.

Salvatierra, J. L., & Rosselli, M. (2010). The effect of bilingualism and age on inhibitory control. *International Journal of Bilingualism*, 15, 26–37. https://doi.org/10.1177/1367006910371021

Sattler, C., Toro, P., Schönknecht, P., & Schröder, J. (2012). Cognitive activity, education and socioeconomic status as preventive factors for mild cognitive impairment and Alzheimer's disease. *Psychiatry Research*, 196, 90–95.

Schweizer, T. A., Ware, J., Fischer, C. E., Craik, F. I., & Bialystok, E. (2012). Bilingualism as a contributor to cognitive reserve: Evidence from brain atrophy in Alzheimer's disease. *Cortex*, 48, 991–996.

Snowdon, D. A. (2003). Healthy aging and dementia: Findings from the Nun Study. *Annals of Internal Medicine*, 139, 450–454.

Soveri, A., Rodriguez-Fornells, A., & Laine, M. (2011). Is there a relationship between language switching and executive functions in bilingualism? Introducing a within group analysis approach. *Frontiers in Psychology*, 2, 183. https://doi.org/10.3389/fpsyg.2011.00183

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the International Neuropsychological Society*, 8, 448–460.

Stern, Y. (2012). Cognitive reserve in ageing and Alzheimer's disease. *The Lancet Neurology*, 11, 1006–1012.

Stern, Y., Albert, S., Tang, M. X., & Tsai, W. Y. (1999). Rate of memory decline in AD is related to education and occupation Cognitive reserve? *Neurology*, 53, 1942–1942.

Stern, Y., Gurland, B., Tatemichi, T. K., Tang, M. X., Wilder, D., & Maveux, R. (1994). *JAMA*, 271, 1004–1010.

Tucker-Drob, E. M., Johnson, K. E., & Jones, R. N. (2009). The cognitive reserve hypothesis: a longitudinal examination of age-associated declines in reasoning and processing speed. *Developmental Psychology*, 45, 431–446.

Wilson, R. S., Boyle, P. A., Yang, J., James, B. D., & Bennett, D. A. (2015). Early life instruction in foreign language and music and incidence of mild cognitive impairment. *Neuropsychology*, 29, 292–302.

Woumans, E. V. Y., Santens, P., Sieben, A., Versijpt, J. A. N., Stevens, M., & Duyck, W. (2015). Bilingualism delays clinical manifestation of Alzheimer's disease. *Bilingualism: Language and Cognition*, 18, 568–574.

Zahodne, L. B., Schofield, P. W., Farrell, M. T., Stern, Y., & Manly, J. J. (2014). Bilingualism does not alter cognitive decline or dementia risk among Spanish-speaking immigrants. *Neuropsychology*, 28, 238–246. https://doi.org/10.1037/neu0000014

Address for correspondence

Ellen Bialystok
Department of Psychology
York University
4700 Keele Street
Toronto, Ontario, M3J 1P3
Canada

ellenb@yorku.ca

Co-author details

John A. E. Anderson
Department of Psychology
York University
Canada

janderz@yorku.ca

John G. Grundy
Department of Psychology
Iowa State University
USA

jggrundy@gmail.com

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