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BRAIN RESEARCH

Research Report

Age effects on load-dependent brain activations in working memory for novel material

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ARTICLE INFO

Article history:
Accepted 5 October 2008
Available online 21 October 2008

Keywords:
Aging
Working memory
Neural compensation
Neural capacity
Inefficiency

ABSTRACT

Three competing models of cognitive aging (neural compensation, capacity limitations, neural inefficiency) were examined in relation to working memory for novel non-verbal material. To accomplish this goal young (n=25) and old (n=25) participants performed a delayed item recognition (DIR) task while being scanned with bold fMRI. The stimuli in the DIR task consisted of computer-generated closed-curve shapes with each shape presented only once in the testing conditions of each participant. This ensured that both the novelty and appearance of the shapes maximized visual demands and limited the extent of phonologic processing. Behaviorally, as expected, the old participants were slower and less accurate compared to the young participants. Spatial patterns of brain activation that corresponded to load-dependent (stimulus set size ranged from 1 to 3) fMRI signal during the three phases of the DIR task (memory set presentation, retention delay, probe presentation) were evaluated in both age groups. Support for neural compensation and capacity limitation was evident in retention delay and the probe phase, respectively. Data were inconsistent with the neural inefficiency model. The process specific support for the theories we examined is consistent with a large corpus of research showing that the substrates underlying the encoding, retention and probe phases are different. That is, cognitive aging theories can be specific to the neural networks/regions underlying the different phases of working memory. Delineating how these theories work in concert can increase knowledge of age-related effects on working memory.

1. Introduction

Working memory refers to the retention and manipulation of information, typically in a time scale of seconds. There is almost a universal consensus that working memory is critical for a range of cognitive abilities including planning (Prabhakaran et al., 2000) reasoning (De Neys and Verschueren, 2006) language comprehension (Baddeley, 1992) general fluid intelligence (Engle et al., 1999a) and problem solving skills (Thevenot and Oakhill, 2006). Traditionally, working memory

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doi:10.1016/j.brainres.2008.10.009

has been divided into verbal and visual buffers subordinate to a central executive system (Baddeley, 1986, 1992) but more recently (Baddeley and Logie, 1999) the visual buffer has been further divided into two components subserving object and spatiotemporal information (see Postle, 2006 for a recent overview concerning previous and current approaches to the study of working memory).

Working memory shows a downward trajectory across the adult lifespan in non-demented individuals (Park et al., 2002) with deficits often observed in paradigms that manipulate memory load (Anders et al., 1972; De Beni and Palladino, 2004; Eriksen et al., 1973; Orsini et al., 1987) and demands on the attention and executive systems (Holtzer et al., 2004, 2005). The latter findings are consistent with the premise that working memory depends on attention resources (Kane et al., 2001; Engle et al., 1999b) that decline with age (Craik and Byrd, 1982). Several studies showed that the negative effect of old age is more pronounced in non-verbal compared to verbal working memory tasks (Jenkins et al., 2000; Myerson et al., 1999). Such findings are consistent with the notion that certain aspects of language and semantic knowledge remain relatively constant across the adult life span (Stine-Morrow et al., 2006). However, evidence for comparable decline in verbal and non-verbal working memory also exists (Park et al., 2002; Salthouse and Babcock, 1991; Salthouse, 1994). The degree to which older adults are familiar with the items to be studied may also mediate the effect of aging on working memory. For instance, previous research found that recollection and familiarity have separate influences on memory performance (Anderson and Craik, 2006; Hay and Jacoby, 1996; Hay and Jacoby, 1999; Jacoby, 1991). Whereas familiarity relies upon automatic activation, recollection is a more effortful process of retrieval that involves executive control and tracking of contextual information (Mulligan and Hirshman, 1997; Steffens et al., 2000). Old age has negative effect on recollection but not on familiarity (Hay and Jacoby, 1999) in effortful and effortless learning paradigms (Anderson and Craik, 2006). In the context of imaging studies examining the effect of aging on working memory it is reasonable to hypothesize that the functional brain circuitry that underlies age-related deficits will vary depending on whether the stimuli used are novel or well-rehearsed and familiar.

Age-related pathological changes in brain structures are ubiquitous (Kemper, 1994; Raz, 2000). Hence, examining from a theory-based perspective whether functional brain circuitry is age variant or age invariant vis-à-vis working memory performance is of interest, especially in light of the existing neuropathology in the aging brain. Two models do not predict qualitative changes in patterns of brain activation with aging. A limited capacity hypothesis predicts that young and old individuals recruit the same brain networks/regions in response to a cognitive challenge but that the elders will show reduced levels of brain activation in those regions. Indeed, reductions in brain activity in aging have been found across cortical regions (Cabeza et al., 2004; Grady et al., 1995; Madden et al., 1996; Reuter-Lorenz et al., 2000); and some age-related reductions in activations were associated with poorer cognitive performance (Jonides et al., 2000; Rypma and D'Esposito, 2000). In contrast, increased activation of networks that is correlated with poorer or equivalent cognitive performance has been considered an indication of age-related neural inefficiency (Rypma et al., 2002; Zarahn et al., 2007).

Alternatively, there are models that do predict qualitative changes in patterns of brain activation with aging compensatory models posit that re-organization of brain circuits in old individuals involving recruitment of new networks and/or underutilization of brain regions activated in young individuals can compensate for the neuropathological consequences of aging (Cabeza, 2002; Cabeza et al., 2002; Grady and Craik, 2000; Stern et al., 2000). As evident from a recent review of imaging studies examining age-related changes in brain activations in working memory, much of this research is focused on the prefrontal cortex (Rajah and D'Esposito, 2005). In that context, the hemispheric asymmetry reduction in old adults (HAROLD) model, an example of a compensatory reallocation model predicting increased bilateral activation in the prefrontal cortex in old compared to young individuals, has stimulated a great deal of research and has garnered empirical support as well (Cabeza et al., 2000; Cabeza, 2001, 2002). Inherent in compensatory reallocation model(s) is the premise that among older adults those who express a brain activation pattern that is age specific to higher degree perform better on cognitive tasks compared to those who express the same pattern to a lesser degree. However, as pointed by Rajah and D'Esposito, (2005) the HAROLD model does not address whether these laterality effects are specific to the prefrontal cortex or are common other brain regions; and nor does it specify the mechanisms underlying neural age-related reductions in lateralized activity.

A less stringent view of compensation would consider a brain pattern compensatory when it is uniquely expressed by an impaired group (such as in aging) but not by an unimpaired group. This approach, which we have termed neural compensation (Stern et al., 2005; Stern, 2006) does not require a direct correlation between expression of a unique age-related brain activation pattern and performance. Rather it acknowledges the possibility that a network recruited in old but not younger individuals may be required simply to support performance in the face of age-related neural changes. Further, it is important to emphasize that neural compensation does not restrict the study of age-related differences in brain activation and compensation of working memory (and of other cognitive functions) to the prefrontal cortex. Often studies have found that concomitant with decreased age-related brain activation in some areas were increased activations in other areas (Cabeza et al., 2004; Milham et al., 2002). This scenario is inconsistent with a simple limited capacity theory or with a simple compensatory reallocation model. However, it is consistent with neural compensation in that a second brain activation pattern that is observed in old but not young individuals may serve to support a first pattern that is common in both age groups. The dedifferentiation hypothesis provides an alternative account of this differential recruitment of brain networks between young and old individuals (Baltes and Lindenberger, 1997; Li and Lindenberger, 1999). In dedifferentiation changes are assumed to be secondary to the deleterious effect of aging on the brain and are not conceptualized as necessarily beneficial to cognitive function. Dedifferentiation implies a breakdown in the optimal state of neurologic organization, or decreased functional integration