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Review

Reliable differences in brain activity between young and old adults: A quantitative meta-analysis across multiple cognitive domains

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ABSTRACT

We conducted a systematic review of the neuroimaging literature examining cognition in old and young adults and quantified these findings in a series of meta-analyses using the activation likelihood estimation technique. In 80 independent samples, we assessed significant convergent and divergent patterns of brain activity across all studies; where task performance was equated or different between age groups; and in four specific cognitive domains (perception, memory encoding, memory retrieval and executive function). Age differences across studies predominantly involved regions within the 'task-positive network' of the brain, a set of interconnected regions engaged during a variety of externally driven cognitive tasks. Old adults engaged prefrontal regions more than young adults. When performance was equivalent, old adults engaged left prefrontal cortex; poorly performing old adults engaged right prefrontal cortex. Young adults engaged occipital regions more than old adults, particularly when performance was unequal and during perceptual tasks. No age-related differences were found in the parietal lobes. We discuss the reliable differences in brain activation with regards to current theories of neurocognitive aging.

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1. Introduction

In recent years, functional neuroimaging has become an ever more popular tool to study the neural correlates of differences in cognitive function between young and old adults. When brain activity in young and old adults is compared on a task, there are at least three possible outcomes in any given brain area: (1) young and old groups could have equivalent brain activity, (2) old adults could show less activity, or (3) old adults could show greater activity. Equivalent activity is generally considered evidence for spared function in the elderly, although if performance is lower in the old group this may indicate less effective use of neural resources (Zarahn et al., 2007). Reduced activity in the elderly can reasonably be assumed to reflect a reduced level of functioning, particularly when accompanied by poorer performance on the task (e.g., Anderson et al., 2000; Grady et al., 2006; Rypma and D'Esposito, 2000). Increased recruitment of brain regions in old compared to young participants is the most intriguing result, but poses a major challenge of interpretation. For example, over-recruitment of brain activity in old adults could potentially be due to compensation, inefficiency in utilization of some neural processes, or a reduction in the differentiation and/or specificity of response during a given task (for reviews, see Cabeza, 2002; Grady, 2008; Rajah and D'Esposito, 2005).

This growing literature on the neuroscience of cognitive aging has suggested that there are some reliable age-related differences in brain activity found across studies. From the earliest experiments in this field, which involved perceptual matching tasks, it was clear that age differences in brain activity could take the form of both decreases and increases of activity in old adults compared to their younger counterparts, with increases found in prefrontal cortex and decreases found in occipital regions (Grady et al., 1994).

Age-related changes in neural activity have been observed across numerous cognitive domains, including perception (e.g. Grady et al., 1994), memory encoding (e.g. Madden et al., 1996), memory retrieval (e.g. Schacter et al., 1996), working memory and executive functions (e.g. Grady et al., 1998). Studies of perception often involve the presentation of a stimulus, paired with a decision about that stimulus. Encoding information is not dissimilar to perception; however, entails later verifying the retention of perceived information. Memory retrieval, on the other hand, involves a test of previously learned information. Finally, working memory and executive functions are examined by a diversity of tasks involving the maintenance and manipulation of information online or response inhibition and selection according to task goals.

Many subsequent studies have replicated age-related increases in frontal cortex (e.g., Cabeza et al., 2002; Madden et al., 1999; Morcom et al., 2003; Nielson et al., 2002; Rosen et al., 2002) and decreases in visual areas (Anderson and Grady, 2004; Davis et al., 2008; Madden et al., 2002, 2004). Increased activity in old adults initially led to the suggestion that additional frontal activity can compensate for reduced activity elsewhere in the brain, providing a benefit to cognitive performance (Cabeza et al., 1997; Grady et al., 1994), and much of the subsequent work has continued to explore this idea. When old adults recruit a brain region or regions that are not active in young adults, but have performance equivalent to that seen in young adults, then the over-recruitment has generally been interpreted as compensatory (Cabeza et al., 1997; Grady et al., 1994, 2008; Reuter-Lorenz et al., 2000). However, other interpretations of over-recruited activity in old adults are also possible. For example, inefficient use of brain activity in old adults has been invoked when there is no age difference in behavior but old adults have more activity in task-related brain regions than do young adults (Morcom et al., 2007; Zarahn et al., 2007). That is, old adults may need to allocate greater neural resources in general, but this may not necessarily translate into better task performance. However, the possibility that this engagement of new areas represents non-selective recruitment or dedifferentiation in the elderly cannot be ruled out entirely (Logan et al., 2002). Indeed, some recent work suggests that over-recruitment of prefrontal cortex is found primarily in old adults who perform poorly on the task at hand (Colcombe et al., 2005; Duverne et al., 2009; Grady et al., in press). Finally, perhaps the strongest evidence for compensation occurs when old adults recruit brain activity that is not seen in young adults, and the engagement of this area or areas is directly correlated with better performance only in the old adults and not in the young (Grady et al., 2002, 2005, 2003; McIntosh et al., 1999; Stern et al., 2005). This would indicate the recruitment of a unique pattern of neural activity that supports task performance in an age-specific manner. At the current time, it seems likely that at least some age-related differences in brain activity are compensatory, but certainly one cannot make this claim for all such differences, and it is not clear how widespread this phenomenon would be across tasks or cognitive domains.

There have been a few reviews and meta-analyses attempting to identify common trends across papers in the aging neuroscience literature (Anderson and Grady, 2001, 2004; Cabeza, 2002; Grady, 1999; Park and Reuter-Lorenz, 2009; Rajah and D'Esposito, 2005; Reuter-Lorenz and Lustig, 2005). Although these have shown what appear to be relatively robust findings across independent studies, primarily related to memory, there has not yet been a meta-analysis using quantitative methods to identify common age-related changes across all the cognitive domains that have been studied. It seemed to us that sufficient data had appeared in the literature for this to be a worthwhile undertaking. In addition, reliable findings across studies could provide information about areas of the brain that are most vulnerable to the effects of aging (i.e., those with age-related reductions in activity) and those that might show the most plasticity (i.e., those with age-related increases in activity) in response to these effects.

In this paper we have carried out a quantitative meta-analysis using the activation likelihood estimation (ALE) approach for neuroimaging data (Laird et al., 2005; Turkeltaub et al., 2002). Because we were looking for age differences that are reliable across cognitive domains, we expected involvement of brain areas that mediate cognitive processes underlying multiple types of tasks. An example of such a set of brain areas is the so-called 'task-positive network' (Fox et al., 2005; Toro et al., 2008), or TPN. The TPN is active during a wide variety of externally-driven cognitive tasks, and consists of regions thought to be involved in attention and cognitive control (e.g., Corbetta et al., 2008; D'Esposito et al., 1995; Dosenbach et al., 2007; Dove et al., 2006; Vincent et al., 2008). The regions generally considered to be part of the network are: (1) dorsolateral prefrontal cortex (DLPFC), rostrolateral prefrontal cortex (RLPFC) and anterior insula/frontal operculum (aIfO); (2) superior parietal cortex near the intraparietal sulcus (IPS) and anterior inferior parietal lobes (aIPL, particularly the supramar-