NeuroImage 172 (2018) 21–30

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Fluid intelligence and gross structural properties of the cerebral cortex in middle-aged and older adults: A multi-occasion longitudinal study

Peng Yuan [a], Manuel C. Voelkle [b,e], Naftali Raz [c,d,e,*]

[a] School of Kinesiology, University of Michigan, Ann Arbor, MI, USA
[b] Department of Psychology, Humboldt University, Berlin, Germany
[c] Institute of Gerontology, Wayne State University, Detroit, MI, USA
[d] Department of Psychology, Wayne State University, Detroit, MI, USA
[e] Max Planck Institute for Human Development, Berlin, Germany

ARTICLE INFO

Keywords:
Aging
Brain
Intelligence
Brain volume
Cortical thickness
MRI
Frontal
Parietal
Temporal
Cognitive aging

ABSTRACT

According to Parieto-Frontal Integration Theory (P-FIT, Jung and Haier, 2007), individual differences in a circumscribed set of brain regions account for variations in general intelligence (*g*). The components of *g*, fluid (G*f*) and crystallized (G*c*) reasoning, exhibit distinct trajectories of age-related change. Because the brain also ages differentially, we hypothesized that age-related cognitive and neural changes would be coupled. In a sample of healthy middle-aged and older adults, we examined changes in G*f* (operationalized by Cattell Culture Fair Test) and G*c* (indexed by two vocabulary tests) as well as in structural properties of 19 brain regions. We fitted linear mixed models to the data collected on 73 healthy adults who participated in baseline assessment, with 43 returning for at least one follow-up, and 16 of them contributing four repeated assessments over seven years. We observed age differences as well as longitudinal decline in G*f*, contrasted to a lack of age differences and stability in G*c*. Cortical thickness and cortical volume exhibited significant age differences and longitudinal declines, which were accelerated in P-FIT regions. G*f* (but not G*c*) was associated with cortical thickness, but no such relationship was found for cortical volume. Uniformity of cognitive change (lack of reliable individual differences) precluded examination of the coupling between cognitive and brain changes. Cortical shrinkage was greater in high-G*c* individuals, whereas in participants with higher G*f* cortical volume slower volume shrinkage was observed.

Introduction

Over a century ago, Charles Spearman hypothesized that general intelligence, or *g* factor, can explain the observed commonality among diverse mental abilities (Spearman, 1904, 1927). Decades later, Spearman's student Raymond Cattell postulated that intelligence was not a unitary entity and introduced the concepts of fluid (G*f*) and crystallized intelligence (G*c*) as independent components of Spearman's g (Cattell, 1943). In contemporary literature, fluid intelligence (G*f*) refers to the capacity for logical reasoning and problem-solving that is presumably independent of acquired knowledge (Cattell, 1971) and is typically evaluated by nonverbal tests such as the Cattell Culture Fair IQ test (CFIT, Cattell and Cattell, 1973), Raven's Progressive Matrices (Raven, 1981), or the performance subscale of the Wechsler Adult Intelligence Scale (WAIS, Wechsler, 1958). Crystallized intelligence (G*c*), in contrast to G*f*, stands for the ability to use acquired and culture-relevant information, and is assessed by tests of vocabulary and general knowledge. Although G*f* and G*c* are viewed as representations of distinct intelligence components, they are not statistically independent (Carroll, 1993) and correlate with each other, usually greater than $r = 0.3$ (Flanagan and McGrew, 1998; Li et al., 2004).

In search for its biological foundations, fluid intelligence has been linked to various brain properties and indicators of brain integrity. For example, patients with lesions in the prefrontal (Roca et al., 2010) and parietal cortex (Woolgar et al., 2010) compared to intact controls evidence lower performance on fluid intelligence tests. Increased functional activation in frontal, parietal and anterior cingulate cortices was observed during fluid reasoning tasks (Geake and Hansen, 2005; Masunaga et al., 2008; Prabhakaran et al., 1997). In the temporal lobe, many regions such as posterior superior temporal gyrus (Luo et al., 2003), inferior and middle temporal gyri (Goel and Dolan, 2004; Knauff et al., 2002), as well as the fusiform gyrus (Goel and Dolan, 2004; Luo et al.,

* Corresponding author. Institute of Gerontology, 87 East Ferry St., Detroit, MI 48202, USA.
E-mail address: nraz@wayne.edu (N. Raz).

https://doi.org/10.1016/j.neuroimage.2018.01.032
Received 22 April 2017; Received in revised form 26 December 2017; Accepted 14 January 2018

2003) also exhibit activation during performance on various fluid intelligence tasks. A recent meta-analysis confirmed the association of gray matter volume in frontal, temporal, and posterior cingulate cortices as well as activation peaks in multiple frontal, parietal, and temporal regions with performance on (predominantly fluid) intelligence tests (Basten et al., 2015).

The described pattern of associations linking multiple cortical regions to G*f* performance served as an impetus for developing the Parieto-Frontal Integration Theory (P-FIT) of fluid intelligence (Jung and Haier, 2007). The P-FIT postulates a complex yet circumscribed network of cortical regions as the brain substrate of cognitive operations that constitute fluid reasoning. The proposed network includes the dorsolateral prefrontal cortex, the inferior and superior parietal lobules, the anterior cingulate gyrus, and selected areas within the temporal and occipital lobes. In P-FIT, the temporal and occipital regions are viewed as part of the G*f* supporting circuitry because of their contribution to the early processing of sensory information; the parietal cortex is included as the module, in which the products of sensory processing are handled after initial processing in the primary cortices and in interaction with prefrontal regions, with the latter deemed crucial for generating an optimal solution to a given problem; and anterior cingulate constrains the selected response and inhibits other competing processes.

Notably, G*f* and G*c* exhibit distinct trajectories of development and aging (Desjardins and Warnke, 2012; McArdle et al., 2002). Fluid reasoning competence improves rapidly during childhood and adolescence, peaks in early adulthood, and gradually declines throughout the later part of the life span thus acquiring a status of a quintessential age-sensitive ability (Horn and Blankson, 2005). Crystallized intelligence rises during early development and schooling, but does not weaken during normal aging, and may even continue to improve after G*f* peaks and starts to wane (McArdle et al., 2000). It follows from P-FIT that decrements in G*f*, but not G*c*, should be associated with a breach of integrity in any component of the outlined network.

Normal brain aging presents an opportunity for testing this proposition. The cumulative research on healthy aging unequivocally demonstrates that it profoundly alters structural characteristics of the brain, even in the absence of age-related disease (see Fjell et al., 2014; Kennedy and Raz, 2015; Raz and Rodrigue, 2006 for reviews). Moreover, the extant studies converge on the pattern of brain aging that corresponds to the network of structures specified in P-FIT theory of neural bases of intelligence. Thus, it is plausible that cognitive aging characterized by decrements in fluid intelligence would be linked to age-related changes in specific brain structures comprising the P-FIT network.

To date, testing this hypothesis has been hampered by the lack of longitudinal evidence that is necessary for assessment of the brain and cognitive aging and their relationship (Hofer and Sliwinski, 2001; Lindenberger et al., 2011; Maxwell and Cole, 2007). Although a recent longitudinal study has reported coupling of changes in brain structure and G*f* (Persson et al., 2016), it was limited to two measurement occasions. The current study aimed at evaluating the relationship between longitudinal changes in G*f* and in gross structural properties of the cerebral cortex in a sample of middle-aged and older adults who have been assessed up to four times over a relatively long period. Our objectives were as follows.

First, we modeled change in G*f* and G*c* over time, and evaluate individual differences therein. Second, in the same fashion, we modeled change and individual differences in change of cortical thickness and volume in the cortical regions specified by P-FIT theory, while contrasting distinct regions that are considered the brain substrates of G*f* with the sensory and motor regions regarded as controls. Third, we assessed the relationship of G*f* with regional volume and cortical thickness. Finally, depending on the presence of statistically reliable individual differences in change, we planned to examine the coupling of brain and cognitive changes and lead-lag relationships between changes in these two domains.

Based on the surveyed literature, we hypothesized that G*f*, but not G*c*, would be negatively related to age at baseline and would decline over time. Likewise, we expected smaller cortical volume and thickness in older participants at baseline and significant reduction of both over the follow-up period. In addition, we hypothesized that shrinkage of the tertiary association cortices - prefrontal and parietal - would accelerate over time. Furthermore, better G*f* performance was hypothesized to be associated with larger and thicker prefrontal and parietal association cortices and change in G*f* was expected to be coupled with cortical changes in the regions identified in P-FIT as critically important for fluid intelligence. In evaluating associations between structural parameters of the cortex and fluid intelligence, we took advantage of a multi-occasion longitudinal design with a theoretical maximum of 5548 data points[1] and planned to examine whether steeper decline in G*f* would be associated with faster thinning of association cortices and whether changes in the brain structure led or trailed changes in G*f*. The latter would depend on finding individual differences in change of the relevant the variables.

Methods

Participants

Participants were healthy volunteers from the metropolitan Detroit area. They attained at least high school education, were native English speakers and exhibited strong right-hand preference (75% and above on the Edinburgh Handedness Questionnaire; Oldfield, 1971). Persons who reported a history of cardiovascular disease, neurological or psychiatric conditions, diabetes, head injury with a loss of consciousness for more than 5 min, thyroid problems, history of drug and alcohol abuse were excluded from participation in the study. Persons who were taking anti-seizure medication, anxiolytics, or antidepressants were excluded as well. Mini-Mental State Examination (MMSE) (Folstein et al., 1975) and Center for Epidemiologic Studies Depression Scale (CES-D) (Radloff, 1977) were used to screen probable cases of dementia and depression, and only participants who scored at least 26 on MMSE and below 16 on CES-D were enrolled in the study. All participants provided informed consent for participation in this study, which was approved by university human investigations committee.

The pool of eligible participants (see Table 1 for descriptive statistics) consisted of 73 persons, age 49 years and older, of whom 43 returned for at least one follow-up. Three additional participants who were assessed at baseline but did not return were excluded because they did not meet the health criteria: two had cancer and the third one had a colloidal cyst in the brain. The participants who returned for follow-ups did not differ from the rest of the pool in age, education, sex, ethnicity, and hypertension diagnosis (all $p > .45$). However, the 43 individuals returning for follow-up measures had higher MMSE than the 30 who did not return: $M \pm SD$: 28.9 ± 1.1 vs. 28.0 ± 1.1, $t\,(71) = 3.188$, $p = .002$.

Cognitive measures

Fluid intelligence. The Cattell Culture Fair Intelligence Test (CFIT, Form 3B, Cattell and Cattell, 1973) was administrated to measure fluid intelligence. The test consists of four subtests, each containing 10 to 14 nonverbal reasoning problems of a gradually increasing difficulty. The subtests cover various aspects of abstract reasoning such as detecting similarity in designs, completing matrices, and solving nonverbal syllogisms, with participants having to derive the rules required for solving the problems. Participants could finish the entire tests, but the items that had been completed at standard times allotted to each subtest were recorded and used for computation of the total timed score that was used in the following analyses.

Crystallized intelligence. G*c* was assessed by two multiple-choice vocabulary tests (V-2 and V-3) from the Educational Test Services Kit of

[1] 19 brain areas × 73 participants × 4 time points.