Using fNIRS to identify age-related neurocognitive changes in working memory (Literature Review)

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Background

As advances in medicine and public health measures, among other factors, have lengthened the average lifespan of humans, the proportion of older adults (aged >65 years) within the population is rapidly increasing (Cabeza et al., 2018). A decline in cognitive function is considered an inevitable consequence of the ageing process. Even in healthy ageing adults, a small yet noticeable decrease in most aspects of cognition is evident, particularly in processes that involve inhibition or memory (Jamadar, 2020). There is variation in the trajectory in which people age: some individuals in their 70s, 80s, and 90s show little decline in their cognitive function, which can be considered healthy or optimal ageing. Conversely, others show drastic cognitive decline early on (in their 50s and 60s), which can progress into memory-related diseases such as Alzheimer's disease (Jamadar, 2020).

One of the most urgent goals in the area of cognitive neuroscience is to understand why some individuals experience a more rapid decline in their cognitive functioning compared to others (McDonough et al., 2022). From a biological perspective, the ageing process is accompanied by changes in the functional and structural integrity of the brain (Grady, 2012). The neural mechanisms that can potentially explain age-related changes in cognition exist at many levels (cellular and molecular) and include factors such as brain atrophy or white matter degredation (McDonough et al., 2022; Cabeza et al., 2018).

Investigating age-related differences in brain activity has become much more feasible with the recent use of non-invasive neuroimaging methods, such as functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) (McDonough et al., 2022). Research using neuroimaging technology has reported distinct brain activity differences between old and young adults, which is shown to be linked to differences in cognitive performance (McDonough et al., 2022; Cabeza et al., 2018). However, there are discrepancies in the recent literature in regard to whether brain activity differences are positively associated with cognitive performance (Nyberg et al., 2009; Mattay et al., 2006; Cabeza et al.,

2002), or whether they are negatively associated with performance (Park et al., 2010; Li et al., 2001). Therefore, further research using neuroimaging is needed to better understand how theses age-related brain activity differences affect cognitive performance (McDonough et al., 2022; Cabeza et al., 2018).

Use of fNIRS to Study Age-Related Neurocognitive Changes

fNIRS technology is a non-invasive neuroimaging method used for studying brain activity in individuals across different age groups. Compared to other imaging techniques like fMRI, fNIRS offers better temporal resolution and lower sensitivity to body movements (Pinti et al., 2020). It operates by emitting near-infrared (NIR) light at varying wavelengths (between 650-950nm) from a transmitter, which penetrates the layers of the head (skin, skull, cerebrospinal fluid) and reaches the cortical brain tissue. The light is then attenuated, absorbed, and scattered, and these changes are detected by corresponding receivers (Pinti et al., 2020). By measuring the concentrations of oxygenated hemoglobin (HbO2) and deoxygenated hemoglobin (HbR), fNIRS serves as a proxy for cortical activity (Pinti et al., 2020). This technology allows researchers to examine changes in brain activity in different regions as an individual ages, which is why fNIRS is an optimal brain imaging technique for examining these age-related changes in targeted brain areas.

While many studies have primarily examined brain activity within the prefrontal cortex (PFC) of the frontal lobe (Yeung et al., 2023; Nguyen et al., 2019; Vermeij et al., 2014), more recent studies have employed brain imaging technologies such as fMRI and fNIRS to study multiple brain regions at once (Kato et al., 2017; Kito et al., 2014; Heinzel et al., 2013), which allows for the measurement of functional connectivity in the brain. Studying functional connectivity rather than focusing on individual brain regions is crucial for understanding age-related changes in the brain as this allows researchers to examine the coordinated activity and communication patterns between different brain regions, providing a more comprehensive view of the brain's functional organization (Ferras-Permayner, 2019). Recent research which measures brain activity in frontal and parietal regions to examine frontoparietal connectivity using fNIRS has indicated that these changes in brain activity occur not only in the frontal lobe, but exist in the parietal lobe as well (Meidenbauer et al., 2021; Yuk et al., 2020; Fishburn et al., 2014). These

results highlight the importance of using fNIRS to examine functional connectivity of the frontoparietal lobe and how brain activity is conveyed through these neural pathways.

Theories of Brain Aging

Neuroimaging research has identified at least four distinct age-related patterns that characterize the structural and functional changes across various cognitive domains (McDonough et al., 2022). These patterns include: maintenance, neural inefficiency, de-differentiation and neural compensation.

The Brain Maintenance theory states that some older adults display preserved brain structure and function similar to young adults (Reuter-Lorenz & Park, 2014; Nyberg et al., 2012). There are numerous studies whose findings align with the Brain Maintenance theory and show preserved cognitive functioning in older adults, which is demonstrated as similarities in brain activation patterns between old and young adult groups (Geerligs et al., 2014; Chanraud et al., 2013; Davis et al., 2011; Vallesi et al., 2011). The Scaffolding Theory of Aging and Cognition (STAC), proposed by Park & Reuter-Lorenz (2009), further describes the Brain Maintenance theory by suggesting chronological age is not the main factor of changes in brain functioning throughout the lifespan. Neural insults can occur at any age, such as white matter degradation or dopamine depletion, and can subsequently cause alterations in brain functioning (Park & Reuter-Lorenz, 2009). A recently revised STAC theory further explains that life experiences, such as stress, fitness, and education, can also affect whether brain degredation or preservation occurs (Reuter-Lorenz & Park, 2014).

The De-differentiation model is based off the process of de-differentiation or desegregation, which refers to brain activity becoming less distinct or selective with age (Koen & Rugg, 2019). This de-differentiation is thought to be caused by GABA deficiency, which is an inhibitory neurotransmitter (Lalwani et al., 2019), as well as the loss of dopamine receptors in PFC and striatal brain regions, which help regulate attention to specific details (Li et al., 2001). De-differentiation can be characterized as additional activity or attenuation (Park et al., 2012). Two main patterns of de-differentiation can occur: under-recruitment and selective recruitment (McDonough et al., 2022). Research done by Grady et al. (2016) reported that brain networks in

young adults show distinct patterns of temporal fluctuations when engaged in a task, while only a portion of these networks are recruited in older adults during the same task; this can be characterized as under-recruitment. Conversely, research done by Park et al. (2004) reported that brain regions which selectively activated in response to specific stimuli, such as the ventral visual cortex in response to visual objects and faces, did not activate as selectively in older adults compared to younger adults; this can be characterized as selective recruitment. Researchers have found this de-differentiation pattern of brain activity to be associated with lower levels of cognition and poorer task-related performance and is assumed to be negatively associated with cognitive performance (Park et al., 2010; Li et al., 2001).

On the other hand, the Neural Compensation theory suggests that age-related increases in neural activity, particularly in the PFC, are positively associated with cognitive performance and therefore benefit cognition (Spreng & Turner, 2019; Cabeza et al., 2018; Reuter-Lorenz & Park, 2014; Davis et al., 2007; Greenwood, 2007). Researchers have observed that older adults demonstrate bilateral brain activity when performing cognitive tasks, where both hemispheres are active; in contrast, younger adults show lateralization for the same tasks, which is when one hemisphere is active (Cabeza, 2002). The Hemispheric Asymmetry Reduction in Older adults (HAROLD) model proposes that this bilateral activation is used as a compensatory mechanism to counteract age-related cognitive decline, particularly in tasks requiring PFC activation (Cabeza, 2002). Compensation can be defined as the enhancement of cognitive performance by the recruitment of additional brain networks (Cabeza et al., 2018). In terms of behaviour, these compensatory mechanisms allow older adults to perform at a similar level to younger adults during cognitive tasks. Thus, compensation, which is characterized as bilateral brain activity, seems to benefit older adults' performance (Cabeza et al., 2018; Cabeza, 2002). For example, previous research findings show that low-performing older adults recruit similar networks to younger adults but do not perform as well, whereas high-performing older adults use bilateral activation (Cabeza et al., 2002). This supports the idea that bilateral activation allows older adults to perform comparatively to younger adults. Other studies, however, have not found support for the HAROLD model and suggest that bilateral activity is not compensatory but rather reflects the inability to use neural resources effectively (Knights et al., 2018; Morcom & Henson, 2018). Thus, more research is needed to better characterize the role of bilateral brain activity in older adults and how it influences cognitive performance.

Compensation found in older adults has been characterized in several different ways. Researchers have reported compensation is characterized by bilateral prefrontal cortex (PFC) activation during cognitively demanding tasks (Reuter-Lorenz & Cappell, 2008; Cabeza, 2002) paired with lower brain activity in the sensory cortex, which is referred to as the Posterior-to-Anterior Shift in Aging (PASA) (Davis et al., 2007). Compensation has also been characterized as bilateral PFC activity coupled with medial temporal lobe (MTL) activation as well as decreases in nearby white matter (Daselaar et al., 2013) or regions in the default mode network (Spreng & Turner, 2019). Additionally, recent research has found that increases in frontoparietal brain activity are correlated with age-related structural degradations or atrophies in the PFC and MTL, or the inability to regulate the default mode network (Spreng and Turner, 2019; Park and Reuter-Lorenz, 2009; Davis et al., 2007; Greenwood, 2007; Li et al., 2001). These finding aided in the development of the Atrophy Compensation Hypothesis, which suggests that compensatory neural activity in older adults should occur in contralateral or opposite brain regions to sites of brain atrophy in order to minimize the effects of cognitive decline (McDonough & Madan, 2021).

According to Cabeza et. al (2018), there are three potential causes of compensation that can occur: up-regulation, selection, and re-organization. Compensation by upregulation can be defined as the increase or up-regulation of neural resources in response to increasing task demands, which is positively correlated with cognitive performance (Spreng et al., 2010). Compensation by selection explains that older adults will recruit different brain regions than younger adults which may not be as efficient but may be less cognitively demanding and may also benefit performance (Daselaar et al., 2006). Finally, compensation by re-organization occurs when older adults recruit neural mechanisms that are not available to younger adults to compensate for age-related cognitive decline (Cabeza et al., 2002). According to Cabeza et al. (2018), these types of compensation are not mutually exclusive and may co-occur in an individual.

The Neural Inefficiency theory contradicts the Neural Compensation theory as it proposes that an increase in brain activity relates to poorer cognition with aging (Logan et al., 2002; Reuter-Lorenz et al., 2001). Based on this theory, brain activity is thought to increase due to deficits in inhibitory neural circuitry (Lalwani et al., 2019) or low white matter integrity (Bennett & Rympa, 2013). Recent research has found supporting evidence that aligns with the Neural

Inefficiency theory and therefore contradicts the predictions of the Neural Compensation theory. For example, Morcom & Henson (2018) conducted a study that aimed to test the predictions of PASA, which supports the Neural Compensation theory, and instead found brain activity patterns consistent with the Neural Inefficiency model. In the older adult sample, increases in PFC activity were found in both tasks, however cognitive performance was reported to be lower in the older adult sample compared to the younger sample (Morcom & Henson, 2018). These findings suggest that increases in brain activity in the older adult sample were negatively associated with cognitive performance.

There is a very limited amount of evidence in the literature to support the idea of neural inefficiency, which highlights the need for future research (Nguyen et al., 2019; McDonough et al., 2015; Lustig et al., 2009). This pressing need for research is present in all four theories of brain aging, as the significant discrepancies in the literature make it unclear which theory of brain aging has the most empirical support. Therefore, progress should be made towards a revised model of brain aging which integrates and links the current models.

Cognitive Performance and its Relationship to Cognitive Load & Task Complexity

Since age-related differences in brain activity have been found to be dependent on the difficulty of a task, particularly in the PFC, manipulating task complexity is essential in understanding age-related neurocognitive changes (Cabeza et al., 2018; Grady, 2012). The Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH) model proposes that as task difficulty or task load increases, more brain regions will be activated (Mattay, 2006; Reuter-Lorenz et al., 2000). As the Neural Compensation theory suggests, increases in task complexity lead to an increase in neural resource recruitment to meet increasing cognitive demands while maintaining performance; however, the CRUNCH model suggests there might be a threshold of task complexity. CRUNCH predicts this compensatory over-recruitment of neural resources cannot be maintained at high task demands once this threshold has been reached, which leads to poorer performance as well as a reduction in brain activity (Nyberg et al., 2009; Mattay et al., 2006). Furthermore, the CRUNCH model proposes that older adults reach this task load threshold sooner than younger adults. Therefore, during an easy or intermediate task, older adults will recruit more neural resources compared to younger adults in order to compensate and

maintain performance. However, during a difficult task with a high task load, this threshold will be reached and the over-recruitment mechanisms being employed will not be able to be sustained, leading to reduced brain activity and poorer performance in older adults (Reuter-Lorenz & Cappell, 2008).

To test the predictions of the CRUNCH model, it is necessary to manipulate three or more levels of cognitive load in order to determine if there is a task load threshold present, and whether this threshold is being reached sooner in older adults (Mattay et al., 2006). While a very limited number of studies have tested the predictions of the CRUNCH model, recent research has found supporting evidence (Bauer et al., 2015; Toepper et al., 2014; Mattay et al., 2006). For example, Schneider-Garces et al. (2010) used a verbal working memory task and found that older adults showed increased brain activity at low task loads and reduced brain activity at high task loads in the frontoparietal network, whereas young adults demonstrated a linear trend of increasing brain activity with increasing task load.

While there has been some recent support to validate the predictions of the CRUNCH model, other recent studies have found contradicting results. Jamadar (2020) used fMRI technology to examine brain activity in older and younger adults while manipulating task complexity in order to test the CRUNCH model. The results demonstrated a linear increase in brain activity in both older and younger adults at both low and high task loads, which contradicts the predictions of CRUNCH (Jamadar, 2020). Additionally, research done by Blum et al. (2021) reported that older adults were able to maintain compensatory over-recruitment of neural resources at high task loads. These inconsistencies make it difficult to characterize age-related brain activity differences and the role of compensation in relation to task complexity. This highlights the need for future research which manipulates cognitive load to determine whether the increases in brain activity seen in older adults is limited to a certain level of task difficulty, or whether these over-recruitment strategies are maintained regardless of task complexity.

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