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The association of physical activity to neural adaptability during visuo-spatial processing in healthy elderly adults: A multiscale entropy analysis

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ABSTRACT

Physical activity has been shown to benefit brain and cognition in late adulthood. However, this effect is still unexplored in terms of brain signal complexity, which reflects the level of neural adaptability and efficiency during cognitive processing that cannot be acquired via averaged neuroelectric signals. Here we employed multiscale entropy analysis (MSE) of electroencephalography (EEG), a new approach that conveys important information related to the temporal dynamics of brain signal complexity across multiple time scales, to reveal the association of physical activity with neural adaptability and efficiency in elderly adults. A between-subjects design that included 24 participants (aged 66.63 ± 1.31 years; female = 12) with high physical activity and 24 age- and gender-matched low physical activity participants (aged 67.29 ± 1.20 years) was conducted to examine differences related to physical activity in performance and MSE of EEG signals during a visuo-spatial cognition task. We observed that physically active elderly adults had better accuracy on both visuo-spatial attention and working memory conditions relative to their sedentary counterparts. Additionally, these physically active elderly adults displayed greater MSE values at larger time scales at the Fz electrode in both attention and memory conditions. The results suggest that physical activity may be beneficial for adaptability of brain systems in tasks involving visuo-spatial information. MSE thus might be a promising approach to test the effects of the benefits of exercise on cognition.

1. Introduction

Aging and its relation to inefficiency in human brain functioning have been widely investigated (Churchill et al., 2002; Grady, 2012; Hedden & Gabrieli, 2004). Notably, while aging might generally impact cognitive functioning, it affects certain neural systems disproportionately (Friedman, 2003; Nyberg et al., 2010). For example, visuo-spatial ability, executive control and working memory have been found to be more vulnerable to aging than other cognitive functions (Hedden & Gabrieli, 2004; Shay & Roth, 1992; West, 1996). These age-related and uneven declines in cognitive abilities are likely a consequence of non-identical regional loss in brain volume, with evidence showing prefrontal cortex or hippocampus being more affected by aging relative to other regions such as the occipital cortex (Hedden & Gabrieli, 2004). In addition, a recent

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model has reported that changes in subcortical areas such as the cerebellum, which works jointly with the frontal lobe, are also a contributing factor to the effects of aging in cognition (Hogan et al., 2011). As such, converging evidence highlights a greater decline in the frontal lobe, along with its associated cognitive functions in later adulthood.

Despite such decline during older adulthood, there is a growing body of evidence showing that exercise or physical activity can prevent or delay age-related loss of brain function (Erickson, Gildengers, & Butters, 2013; Erickson et al., 2010; Hillman, Erickson, & Kramer, 2008; Kramer et al., 1999; Voss et al., 2012) or neurodegenerative diseases (Hamer & Chida, 2009; Sofi et al., 2011). Interestingly, this beneficial effect is selectively larger for frontal-related functions such as executive control (Colcombe & Kramer, 2003; Kimura, Yasunaga, & Wang, 2012; Kramer et al., 1999; Tsai, Wang, et al., 2014), where such loss is most evident. For example, Hillman et al. (2006) reported that, in elderly adults, higher levels of physical activity are related to better task performance in tasks involving greater amounts of executive control. Similar to this, in terms of electrophysiological findings, Hillman, Belopolsky, Snook, Kramer, and McAuley (2004) observed that elderly adults that are more physically active exhibited enhanced frontal P3 amplitude selectively during a condition requiring higher amounts of executive control. These findings all suggest that physical activity may be able to compensate for the larger age-related degenerations in both cognitive and brain functions typically seen with aging.

Although numerous studies have assessed the effects of physical activity on cognition in elderly adults using analysis of mean neurophysiolgocial (e.g., event-related potentials, ERPs) or neuroimaging signals (Erickson et al., 2010; Hillman et al., 2008; Kramer & Erickson, 2007), the investigation of within-individual brain signal complexity or variability has been limited. Signal complexity reflects some aspects of changes in magnitude from moment to moment in neurophysiological time series (Costa, Goldberger, & Peng, 2002, 2005; Garrett et al., 2013; Goldberger, Peng, & Lipsitz, 2002). This type of measure can provide information different from that acquired via mean signals (Garrett, Kovacevic, McIntosh, & Grady, 2012; Hogan et al., 2006) and is considered to reflect neural adaptability and efficiency during cognitive functioning (Garrett et al., 2013; Heisz, Shedden, & McIntosh, 2012; Hogan et al., 2012; Liang et al., 2014; Yang et al., 2013). Mounting evidence has demonstrated the utility of measuring brain signal complexity for the investigation of various physical and mental states, including developmental and aging processes (Garrett et al., 2012, 2013; O'Hora et al., 2013), diseases (Catarino, Churches, Baron-Cohen, Andrade, & Ring, 2011; Hogan et al., 2006), and cognitive performance (Liang et al., 2014). In addition, studies using analysis of brain signal variability may also provide some insight into the relationship between reduced brain complexity and aging (Garrett et al., 2013 for a review). One notable study by Garrett, Kovacevic, McIntosh, and Grady (2010), examining the standard deviations (SDs) of BOLD (blood oxygen level-dependent) signals in young and elderly adults during fixation blocks, reported that the brain signals in elderly adults were generally less varied relative to those in younger adults, possibly reflecting an age-related decrease in network complexity and integration. In addition, studies using calculation of sample entropy also support this argument (Garrett et al., 2013; Hogan et al., 2012). Sample entropy, in short, is a modification of Shannon's entropy (Shannon and Weaver, 1949) and Pincus' appropriate entropy (Pincus, 1991), which calculates the repetitions of similar sequences in a physiological time series signal (Hogan et al., 2012; Richman & Moorman, 2000). Thus, the more unpredictable the dynamic signals are, the higher the values of sample entropy would be, and vice versa. Sample entropy has also been examined in relation to aging and declined brain functioning; Hogan et al. (2012) observed that cognitively-declined older adults tend to show lower entropy during memory encoding than do healthy elderly individual, suggesting that the sample entropy measure may reveal differences in brain complexity with regard to some subtle brain state differences between a healthy and a declined brain. These important investigations suggest that aging-related decline in cognitive function may be due, in part, to changes in the complexity of neural systems.

Is higher complexity better? Here it is important to note that complex systems are neither absolutely deterministic nor completely random (Costa et al., 2005; Tononi, Edelman, & Sporns, 1998); that is, there is no direct association between regularity and complexity (Feldman & Crutchfield, 1998). Thus, enhanced irregularity in the measure of sample entropy is not necessarily synonymous with an increase in intrinsic physiological complexity (Costa et al., 2002, 2005; Goldberger et al., 2002). In such cases, it is suggested to be better to evaluate a loss of physiological complexity by using scaling approaches or other techniques (Goldberger et al., 2002; Peng, Havin, Stanley, & Goldberger, 1995). A fractal scaling measure of physiological complexity, multiscale entropy (MSE), that calculates sample entropy across multiple coarse-grained sequences (Costa et al., 2002, 2005; Heisz et al., 2012; Liang et al., 2014), seems to better meet the criteria of a complexity measure (Tononi et al., 1998). MSE evaluates the occurence of repetitive patterns of each timescale as an index of signal complexity. Higher MSE values thus would signify that the signal is less predictable and information rich, whereas lower MSE values would imply that the time series is more regular and less complex (Costa et al., 2002, 2005; Garrett et al., 2013; Yang et al., 2013). The time scale is defined as the length of each non-overlapping time window within which the original data are averaged to produce a coarse-grained time series. A small time scale means that the length of non-overlapping time windows is short (e.g. 1 ms) whereas a large time scale implies that the length of non-overlapping time windows is long (e.g. 20 ms). Therefore, within a 1000 ms EEG signal sampled at 1000 Hz, there are 1000 data points for the 1-ms time scale coarse-grained time series and only 50 (1000/20) data points for the 20-ms time scale coarse-grained time series. Entropy values at smaller coarse-grained time series capture short-range temporal irregularity, whereas those at larger coarse-grained time series capture long-range temporal irregularity. Therefore, MSE can provide a more comprehensive complexity measure in comparison to a single time scale (Ueno et al., 2014). In support of this argument, studies investigating cardiac interbeat activity using MSE have observed that, although healthy elderly adults exhibited lower entropy values across all time scales compared to those of healthy young adults, the smallest difference occured at scale one (Costa et al., 2002, 2005). This finding suggested the importance of investigating age-related loss in physiological complexity over different time scales. Similarly, Takahashi et al. (2009) observed age-related differences in MSE values of participants' electroencephalographic (EEG) signals while they were viewing a photic stimulus, in particular for values at larger time scales. The lack of significant MSE modulation by photic stimuli in elderly adults may be indicative of age-related decreases in physiological complexity/functional responses to visual stimuli, and this finding also demonstrates the potential of MSE for the investigation of aging pathophysiology based upon EEG data. More importantly, they observed that, after viewing a visual stimulus, MSE values tended to increase at smaller time scales in elderly adults (e.g., scales of 1–5). For larger time scales in these elderly adults values decreased, in contrast to remaining constant in young adults (e.g., for scales of 10–20). The constant MSE pattern in young individuals may reflect a physiological complexity associated with temporal long-range correlations, while the break down