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Sleep spindles and cognitive performance across adolescence: A meta-analytic review☆

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ABSTRACT

Higher sleep spindle activity generally relates to better cognitive performance in adults, while studies in children often show the opposite. As children become young adults, there is rapid brain maturation and development of higher-order cognitive functions, and therefore investigations within this age group may elucidate the relationship between spindles and cognition in this developmental period. Twelve studies published between 2009 and 2016 were identified. Meta-analyses revealed a positive relationship between spindles and cognition overall ($r = 0.27$), however effects varied depending on cognitive domain. Moderate positive relationships were seen for fluid IQ ($r = 0.44$), working memory/executive function ($r = 0.40$) and speed/accuracy ($r = 0.33$), while full IQ/verbal IQ was not significantly associated ($r = -0.05$). Meta-regressions indicated cognitive domain and spindle characteristic had a small influence over effect sizes, while age and gender did not have a significant influence. The relationship between spindles and cognition in adolescents is likely influenced by individual neural makeup and brain maturation.

Sleep spindles are bursts of synchronised oscillatory neural activity seen via electroencephalography (EEG) that occur throughout various stages of sleep and are believed to be indicators of mental efficiency (Fogel & Smith, 2011). Spindles are associated with diverse cognitive functions, including learning and memory (Fogel, Nader, Cote, & Smith, 2007), intelligence (Fogel & Smith, 2011; Geiger et al., 2011), synaptic plasticity (Urakami, Ionnides, & Kostopoulos, 2012) and sleep-dependent memory consolidation (Clemens, Fabo & Halasz, 2005; Gais, Molle, Helms & Born, 2002; Schabus et al., 2008). Accordingly, the study of spindles and its implications for cognition and intelligence is the focus of increasing research attention. However, the relationship between spindles and cognition in older children and adolescents is less clear, with some studies reporting findings consistent with the adult literature (Bodizs, Gombos, Ujma, & Kovacs, 2014; Geiger et al., 2011), and others finding the opposite relationship (Chatburn et al., 2013; Tessier et al., 2015). The present meta-analytic review will summarise the current empirical literature regarding the relationship between sleep spindles and cognition in adolescents in order to address the gap in the literature regarding this discrete developmental period. Meta-analyses will examine how this relationship might vary according to the cognitive domain measured, how sleep spindles are operationalised, and participant characteristics.

1. What is the current evidence for the relationship between spindles and cognition?

Sleep spindles are characterised by synchronised bursts of typically 10–16 Hz activity (Fig. 1) that arise from interactions between

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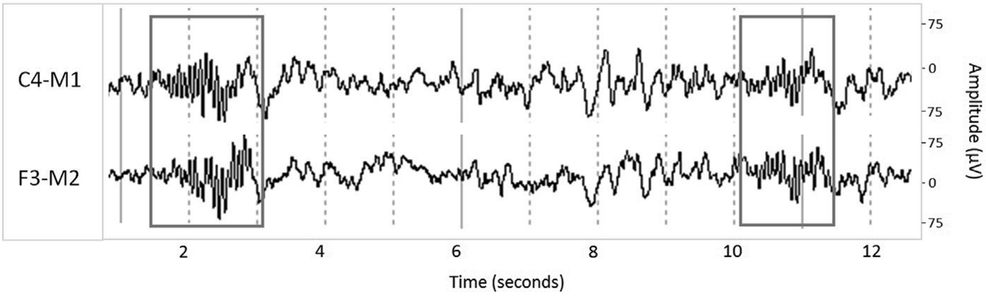

Fig. 1. Sleep spindles in stage 2 seen over both central (C4) and frontal (F3) EEG derivations. Sleep spindle parameters include total number of spindles per sleep episode, average spindle frequency (Hz), average spindle amplitude, average duration (e.g. seconds), density of sleep spindles (number per time period, e.g. per minute), spectral power in the sigma frequency band (11–16 Hz) and an estimated calculation of 'spindle activity' (e.g., mean spindle duration*mean spindle amplitude; Schabus et al., 2004).

the thalamic reticular nucleus and thalamocortical neurons, which together make up the 'thalamocortical loop' (Steriade, 2006). Given the role of the thalamocortical network in information processing and encoding during wakefulness (Bear, Connors, & Paradiso, 2007), it is believed that spindle-related activity of the thalamocortical network during sleep is related to cognitive processes such as memory integration, information processing and intelligence (Fogel & Smith, 2011).

In adults, sleep spindle characteristics are positively correlated with cognition and intelligence measures (Bodizs et al., 2005; Fogel & Smith, 2011; Fogel et al., 2007; Schabus et al., 2006; Urakami et al., 2012), providing support for the hypothesis that spindles are related to general mental ability (Anderson, 2005; Luthi, 2014). The associations between spindle activity and cognition, along with their shared brain networks, are consistent with the notion that spindles reflect a process by which memory and learning are consolidated during sleep (Fogel & Smith, 2011). For example, spindles have been implicated in both declarative memory consolidation (i.e., memories of facts) and procedural memory consolidation (i.e., memories of how to do things) through investigations of the hippocampus and thalamocortical oscillations (Fogel & Smith, 2011). Furthermore, the common thalamocortical networks employed in both spindle production and cognition allow speculation of a causal relationship, where normal intellectual development may depend on normal spindle production (Fogel & Smith, 2011). An important question remains, however: How do spindles and cognition relate during the discrete developmental period of adolescence?

2. Sleep spindles and cognitive performance across adolescence

While existing research supports a relationship between sleep spindles and cognition in adults, there are several salient reasons why these findings cannot be generalised to youth. Firstly, spindle characteristics change across development from childhood to older adolescence. Spindle duration, density (spindles per time unit) and total number of spindles per sleep period decrease with age, while spindle oscillatory frequency increases over time (Nicolas, Petit, Rompre, & Montplaisir, 2001; Shinomiya, Nagata, Takahashi, & Masumara, 1999). Second, the nature of the relationship between spindles and cognition is not uniform among samples of different ages. For example, in a sample of 3- to 5-year-old children, Kurdziel, Duclos, and Spencer (2013) found memory performance negatively correlated with spindle density, which is opposite to the effect witnessed in adults (Cox, van Driel, de Boer, & Talamini, 2014; Lafortune et al., 2014). At preschool ages, lower spindle density may be linked to more mature, rather than less mature, brain development (Tarokh, Carskadon, & Achermann, 2014), indicating a change in the direction of effect from childhood to adulthood. Given the lack of consensus regarding the relationship between spindles and cognition in young people, it is beneficial for the field to gain a picture of the relationship that might be occurring. Furthermore, an examination of adolescent samples might add to the understanding of this phenomenon across age groups.

3. Are there factors that moderate the relationship between sleep spindles and cognition?

There are several factors that may influence the relationship between sleep spindles and cognitive performance. One of these is the way spindles are operationalised. For example, previous studies have compared cognitive measures with total spindle number, frequency, amplitude, duration, density, sigma power and 'spindle activity' (see Fig. 1 for more detail). Some have further divided spindles into 'fast' and 'slow' depending on relative frequencies (e.g. slow spindles < 13 Hz, fast spindles > 13 Hz). This distinction illustrates differences within the spindle-cognition relationship, where slow spindles relate more strongly to procedural performance (Astill et al., 2014) while fast spindles relate to more complex skills such as fluid intelligence (Bodizs et al., 2014).

The relationship between spindles and cognition may also vary according to cognitive measure. For example, some studies have used singular cognitive tests, while others use a cognitive battery such as an IQ test to provide multiple cognitive outcome measures. Original IQ tests grouped cognition under umbrella terms of 'performance intelligence (IQ)' and 'verbal intelligence (IQ)' (Wechsler, 1958). Performance IQ includes cognitive areas of fluid reasoning, spatial processing and visual-motor integration, while verbal IQ includes areas such as verbal comprehension, general knowledge, arithmetic and vocabulary. In adults, total number of spindles and spindle density have shown the strongest relationships with performance IQ tests, while the weaker or non-significant relationships are seen for verbal IQ (Fogel et al., 2007; Nader & Smith, 2003). Lastly, it is possible that age may affect the relationship, with