Cognitive and Brain Development: Executive Function, Piaget, and the Prefrontal Cortex

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Abstract  
Piaget was the first psychologist to systematically investigate cognitive development by proposing the theory of constructivism and thereby creating a new approach to examine learning. He stated that children think and reason differently at distinct periods in their lives. Based on this theory, educators and researchers have been exploring the idea of staggered childhood development of cognition and learning. However, there has been a distinct lack of consideration of the concurrent anatomical and physiological development of the brain. This literature review explores the Piagetian and neo-Piagetian theories in the context of recent findings concerning anatomical and physiological brain development with respect to executive function development. This review suggests that Piagetian development theory may be closely aligned with changes in the anatomical and physiological development of the brain—in particular, the prefrontal cortex and its associated connections. The maturation of an individual’s brain and increases in its complexity during childhood and adolescence appear to occur in stages that parallel the stages of cognitive development identified by Piaget.  

Keywords: cognitive development, Piaget, prefrontal cortex, executive function  

Introduction  
Academic achievement has a significant impact on life outcomes such as occupational success, socio-economic status and life expectancy (Blair & Razza, 2007; Eigsti et al., 2006; Moffitt et al., 2011; Schmidt & Hunter, 1998). Underlying the development of academic achievement, however, is a student’s cognitive and general development during childhood, which in turn relates to developments within the brain (Blair & Razza, 2007; McClelland et al., 2014). This article aims to trace the interrelatedness of key developments in the brain (specifically working memory) and its relationship to achievement. The interaction between our brain development and learning
from our environment increases in complexity during childhood and adolescence (Blakemore & Choudhury, 2006; Crone, 2009; Steinberg, 2005). Some have argued that there are discrete stages of development, others that development is a continuous process, and still others that there is intermingling of both discrete and continuous development.

The concept of discrete and staged development was a key part of Piaget’s theories, whereby he claimed that children think and reason differently at different periods in their lives (Piaget & Cook, 1953). He described the following four stages: the Sensorimotor, the Pre-Operational, the Concrete Operational, and the Formal Operation stages (Piaget & Cook, 1953; Piaget & Inhelder, 1969; Piaget, Inhelder & Inhelder, 1973). Many theorists have attempted to further improve Piaget’s original model and in particular, to account for the movement from one stage of development to another (Brainerd & Brainerd, 1978; Keating, 1980; Lourenço & Machado, 1996; Lunzer & Lunzer, 1960; Shayer, Demetriou, & Pervez, 1988). There has been a distinct lack of examination and consideration, however, of the concurrent anatomical and physiological development of the brain during childhood and how these changes relate to the way in which students learn. Over the past decade, there has been a surge of new methods to better understand brain development in humans. In particular, the use of functional neuroimaging has allowed the measurement of anatomically defined brain activity to be recorded while a participant completes a task or activity. These imaging methods commonly include functional magnetic resonance imaging (fMRI), positron emission technology (PET) and multichannel electroencephalography (EEG).

The imaging methods differ on the basis of their ability to determine temporal or spatial information. Positron emission technology and fMRI measure the presence of blood components in a particular area and are therefore better at determining spatial rather than temporal information. Multichannel electroencephalography measures the activation of clusters of adjacent neurons and can measure millisecond increments of brain activity. These techniques have been used individually or in conjunction with each other to link performance during cognitive function tasks and tests with particular regions of the brain (Gosseries et al., 2008).

This review aligns recent findings in neurobiology with neo-Piagetian cognitive development theory. The claim is that the chronological development of executive function plays a major role in the development and transitions between neo-Piagetian stages (c.f., Blakemore & Choudhury, 2006; Demetriou & Efklides, 1987).

Piagetian theory

The basis for Piaget’s model of cognitive development is four age-dependent stages (Piaget & Cook, 1953; Piaget & Inhelder, 1969; Piaget, Inhelder & Inhelder, 1973). The Sensorimotor stage, from birth to 2 years of age, is where the child exhibits a completely egocentric approach to the world, is unable to separate thoughts from action, and is unable to recognize that the perspective of the object would differ depending on their position relative to object. The child then moves to the Pre-Operational stage from ages 2 to 7 years. In this stage, object permanence is firmly established, and symbolic thoughts develop. In order to move to the next stage, referred to as the Concrete Operational stage (7-11 years), children need to be able to perform what Piaget termed Operations, these are internalized actions that the individual can use to manipulate, transform and then return an object to its original state. The child
understands the principle of conservation, which states that the quantity of an object can be determined to be the same, despite a change in shape or volume of a container. The commonly used example is where the child must determine if an amount of water in two different shaped glasses is the same despite their difference in shape and size. The Concrete Operational stage is also marked by the child beginning to apply logic to steps and stages, assessed through the A not B Task in which an object is hidden from the child in one of two different locations. The final stage from 11 to 16 years, the Formal Operation stage, is characterized by abstract and hypothetical thought.

While there is a large body of literature that supports the underlying principles of Piaget’s theory (Brainerd, 1978; Lourenço & Machado, 1996), there are also a number of weaknesses in Piaget’s work such as: his inability to separate memory from logic (Bryant & Trabasso, 1971); the assumption that children exist at only one stage at a time (Case, 1992; Flavell, 1982); and the impact of cultural context (Dasen, 1975; Dasen & Heron, 1981; Mishra, 1997; Price-Williams, 1981; Price-Williams, Gordon, & Ramirez, 1969).

Neo-Piagetian theorists devised a number of different models to account for these weaknesses. The first theorist to integrate information processing theory with Piaget’s cognitive development theory was Pascual-Leone (1970), who claimed that human thought exists on two levels: the silent operators and the subjective operators. The silent operators were the overarching cognitive hardware, while the subjective operators were the structures and schemas described by Piaget as governing thought. Pascual-Leone argued that mental power (or the ability to simultaneously hold and use independent units of information) increased with age and was the basis for progression through Piagetian stages. This mental power was counteracted by the interrupt operator, which would act to deactivate the subjective operator schemas when required. In order to test a child’s mental power, Pascual-Leone (1970) measured their capacity to hold and repeat a linked series of actions with an associated stimulus. An example of such a test would be to ask the child to raise their hand when they saw a square, or to clap their hands when they saw a red object—the greater the number of sequential action response combinations they could accurately repeat, the greater their mental power.

Case (1992) further developed Pascual-Leone’s two-factor model of cognitive development. However, Case stated that each domain has a different organization (or four sub-domains) and development (the child would transition through all of his four sub-stages before progressing to the next stage of development. A test used by Case (1985) to observe differences in the movement within and between stages is the balancing beam test. For example, from 0-4 months, the child was to simply follow a moving beam with their eyes and their head. By 18 months, they will interact with the object enough to distinguish the effect of push and pull.

Fischer (1980) examined how the environment in which learning takes place affects the actual and optimal level of skill in cognitive development. Like Piaget and Case, Fischer theorized that there were four stages with a recycling pattern of progression through each, but that the difference across domains could be accounted for by the child’s experiences, including their environment. There have been other suggestions (e.g., Demetriou & Efklides, 1987) but none have satisfactorily explained the mechanisms for the changes across the stages. It is the claim of this article that the changes are a function of the development of executive functioning as the brain develops. These developments can be
shown to parallel changes in the brain, which in turn can help explain changes in the ways students process information; especially accounting for the developmental changes that Piaget and the neo-Piagetians have proposed.

**Executive function**

Executive function (EF) is an umbrella term for a set of higher order, general purpose control processes that regulate a number of different cognitive functions (such as thought and behavior) for the attainment of a specific goal (Best, Miller, & Jones, 2009; Diamond, 2012; Karbach & Unger, 2014; Miyake et al., 2000; Titz & Karbach, 2014). Executive function encompasses a wide range of cognitive processes such as working memory, cognitive flexibility, attention control, planning, concept formation, and feedback processing – each varying in complexity (Karbach & Unger, 2014). Executive function is also associated with emotional aspects of growth and development of the child including, but not limited to, moral and communicative behavior and social cognition (Carlson & Moses, 2001; Kochanska, Murray, & Coy, 1997). Further, there is a large evidence base illustrating that the development of EF is a major predictor of scholastic performance (Swanson & Alloway, 2012). In particular, a number of longitudinal studies indicate that EF contributes to academic achievement, rather than vice versa (Best, Miller, & Naglieri, 2011; Bull, Espy, & Wiebe, 2008; George & Greenfield, 2005; Hitch, Towse, & Hutton, 2001; Miller & Hinshaw, 2010).

There is considerable evidence suggesting a developmental pattern of progression in EF occurring among preschool children as young as three (Hughes, 1998) through to adulthood (Huizinga, Dolan, & van der Molen, 2006). In order to identify the differences in these stages, studies have examined the changes in the underlying brain structure as a means of identifying factors that may be involved in the pattern of progression of EF. For example, the age-related developments in EF have been associated with the maturation of a particular area of the brain known as the prefrontal cortex (Diamond, 2002).

Miyake et al. (2000) were among the first to develop a comprehensive multidimensional model of EF. In particular, they created a unity and diversity framework of EF where three fundamental but correlated components were identified (Miyake & Friedman, 2012). The three elements of their model are: inhibition of dominant or proponent responses; updating and monitoring of working memory representations; shifting between tasks or mental sets. The three together form what we call executive functioning.

**Inhibition**

Inhibition is the ability to deliberately inhibit dominant, automatic, or common responses when necessary. For example, inhibition is used when a person is required to say the opposite word associated with a picture, rather than one which might jump to mind immediately. The Stroop Test (Stroop, 1935) is a common form of measuring inhibition — particularly selective attention. Participants are presented with a word which names a color, and are asked to either name the word itself or the color of the ink in which the word is written. This requires the individual to focus on one aspect (the color or the word) while inhibiting the secondary information. By changing the rules midway through an experiment, the Stroop Test can also be used as an indicator of shifting (see below).

**Shifting**

Shifting, also termed cognitive flexibility or task switching, is the ability to move back
and forth between multiple different tasks, operations or mental sets. It is commonly associated with the ability to perform two or more simple “decision” tasks and to switch between them upon a specific cue or in a specific order (Karbach & Unger, 2014). The ability to shift between tasks, or the shift cost, can be measured in two separate components: the response time and the accuracy rate (Best et al., 2009). A slower response time or a decrease in accuracy rate is due to the individual continuing to use the previous pre-switch rules, rather than the new, post-switch rules (Anderson, 2001). Shifting ability can be measured using the Wisconsin Card Sorting Task (WCST) that requires participants to sort cards based on one criteria (e.g., color, shape or image), and then switch at a given point. The switch between the two can either be given explicitly through stating the change of rules or through positive and negative feedback occurring concurrently with the task. Errors associated with shifting are seen when participants are unable to suppress and inhibit the previous set of rules and continue to apply them (Best et al., 2009; Diamond, 2002).

**Updating and monitoring**

Updating and monitoring relates to the subject’s ability to dynamically manipulate the contents being held by working memory. There are a limited number of items of information that can be held at any one time, irrespective of ability; for example, an adult can hold up to three or four items of information in their working memory at any one time (Vogel & Machizawa, 2004). Updating can be measured by the Non-verbal Face Task in which the participant is required to hold and maintain a facial image in their mind and then respond to it after a timed delay (Best et al., 2009). The more difficult tasks include the Spatial Self-ordered Task, where hidden tokens need to be obtained in a pattern and ordered with an ever-increasing difficulty (Best et al., 2009). Due to the range of complexity and modalities of updating, it is critical to identify the reliance on shifting and inhibition involved in the updating task.

**Link to academic achievement**

Across all three factors time is particularly important in cognitive development, and often a more accurate predictor of variability of academic achievement than intelligence and IQ. Indeed, changes in EF contributes to academic achievement rather than versa (Alloway & Alloway, 2010; Altemeier, Abbott, & Berninger, 2008; Andersson, 2008; Swanson, 2004). Executive function improves during the school years, gradually decreasing in the rate of improvement from around age 16 right through to early 30s (Best et al., 2011; Blair & Diamond, 2008; Blair & Razza, 2007; Davidson, Amso, Anderson, & Diamond, 2006; Huizinga et al., 2006; Somsen, 2007; van der Sluis, de Jong, & van der Leij, 2007). It remains to be determined if this gradual improvement occurs in conjunction with the anatomical and physiological development of the brain during childhood.

**Anatomical and physiological brain development**

The progressive development of EF has been linked to the maturation of the underlying anatomy and physiology of the brain. In particular, the development of EF is associated with the maturation of the prefrontal cortex (PFC) and associated cortical and subcortical structures (Bunge & Wright, 2007; Casey et al., 2005; Luna, Padmanabhan, & O’Hearn, 2010). In considering the relationship between EF and neo-Piagetian theories of development, this review will focus on the neurobiological processes known to occur during the post-natal development and maturation of the
brain. This involves two distinct processes: progressive (e.g., neuron growth, synaptogenesis, myelination) and regressive (e.g., cell death, synaptic pruning; Casey, Amso, & Davidson, 2006; O’Hare & Sowell, 2008).

**Brain plasticity**

Changes in the anatomical and physiological connections in the brain are referred to as brain plasticity. This predominantly involves two primary processes which occur at the cellular level that influence the efficacy of cell to cell communication. In the brain, cellular communication involves the release of chemicals (neurotransmitters) across small spaces between adjacent cells known as synapses. The principle processes in brain plasticity involve synaptogenesis and synaptic pruning which together are referred to as synaptic plasticity. Synaptogenesis is the creation of new synapses, or connections, between neurons in the central nervous system. The process occurs throughout childhood development and begins to decrease during ages of sexual maturity (Huttenlocher & Dabholkar, 1997). The process of synaptogenesis involves the overproduction of neurons and connections in the central nervous system (Selemon, 2013). These connections are then honed and refined under the process known as synaptic pruning.

Synaptic pruning is the process of synapse elimination, or the programmed loss of connections between neurons. It is associated with the refinement of connections between neurons by the streamlining and removal of inefficient neural tissue (LaMantia & Rakic, 1984). The elimination of neurons and streamlining of connections in the brain occurs as a result of Hebbian principles (Changeux & Danchin, 1990; Constantine-Paton, Cline, & Debski, 1990; Shatz, 1990; Shatz & Stryker, 1978; Stryker & Harris, 1986). Hebbian principles state that commonly used neural pathways will be strengthened, while those pathways that are not constantly required will be removed. Beginning early in childhood development and ceasing in adulthood, this process is believed to be underpinned by glutamate receptor mediated synaptic plasticity, or what is known as long term potentiation (Selemon, 2013). A difference between the immature brain and the adult brain is the greater number and strength of connections between different parts of the immature brain when compared with the adult brain (Selemon, 2013). Synaptic pruning is considered to be an important biological aspect of brain development as the number of excitatory synapses is two to three times larger in children than in adults (Kolb, Mychasiuk, Muhammad, & Gibb, 2013). It has been suggested that synaptic pruning and elimination are the main reason for a reduction in grey matter or the size and density of the neuron cell bodies identified by neuroimaging techniques (Selemon, 2013). However, it should be noted that the reduction in grey matter may also be associated with the reduction of glial cells and associated cytoarchitecture (Finlay & Slattery, 1983).

There are three types of synaptic plasticity that lead to the development of a mature brain. The first, experience-independent plasticity, is due to genetics and occurs during the pre-natal stage of development (Kolb & Gibb, 2011). The second two types of plasticity—experience-expectant and experience-dependent—are affected by environmental and external circumstances. Experience-expectant plasticity occurs during development and is where the over production of neurons and connections during synaptogenesis is refined based on a demarcated region of connectivity (Kolb & Gibb., 2011). Experience-dependent plasticity involves the modification of synaptic connections associated with learning, experiences, stress or drugs (Blake,
A major neurobiological process that occurs during the post-natal development and maturation of the brain is myelination. Myelination refers to the process of the accumulation of myelin around the axon that increases its thickness and electrically insulates sections of the nerve cell. Myelin is the layer of fatty tissue, or white matter, which surrounds the axon of the neuron allowing for more rapid transmission of signals along that cell. The absence of myelin is associated with a number of neurodegenerative diseases and cognitive impairment (Kiernan & Barr, 2009). As a consequence, its failure to develop or its subsequent degeneration once formed may impact on brain function and development.

The prefrontal cortex

The age-related developments in EF have been linked to the maturation of a particular area of the brain known as the prefrontal cortex (PFC) (Diamond, 2002). The PFC is located in the frontal lobe of the brain, between the central sulcus and the frontal pole (Kiernan & Barr, 2009). It includes Brodmann’s areas 8-13, 24, 27, 32, and 46 described in his cytoarchitecture map of the brain (Brodmann, 1909). A defining characteristic of the PFC is the numerous connections with almost all regions of the cortex and some parts of the lower brain. The connections to the brainstem, thalamus, basal ganglia and limbic system are thought to allow the PFC to play a major role in the cellular inhibition of other areas of the brain (Fuster, 2001). The PFC differs from other areas of the brain in two major ways. First, its relative growth is greater in humans than in other animals (Brodmann, 1912), a distinguishing feature of the human brain. Second, the PFC is one of the last areas of the brain to mature, reaching maturity at about 30 years of age, and it is one of the first areas to show signs of aging (Diamond, 2002; Fuster, 2002; Kolb & Gibb, 2011; Olson & Luciana, 2008).

More generally, the PFC is reported to play a role in learning as it is the primary area that becomes activated at the beginning of the learning sequence or task when the brain is examined using functional neuroimaging (Grafton et al., 1992; Iacoboni, Woods, & Mazziotta, 1996; Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994; Petersen, Van Mier, Fiez, & Raichle, 1998). However, with practice, repetition and routine this activation subsides, and the subcortical structures including the basal ganglia become active (Grafton et al., 1992; Iacoboni et al., 1996; Jenkins et al., 1994; Petersen et al., 1998). There also appears to be a lateralization within the PFC as left/right bias occurs during encoding/retrieval of new information (Fuster, 2001).

Structurally, the PFC can be divided into three distinct areas: the orbital, medial, and lateral aspects (Fuster, 2001). Classification of these areas has been determined by functional neuroimaging research (in combination with deficit models) and the association of the consequences of damage with particular regions. In particular, these studies have found that different EF tasks use slightly different regions of the PFC (Olson & Luciana, 2008), as well as other regions of the brain such as the anterior cingulate cortex (ACC) (Bell & Wolfe, 2004; Bernstein & Waber, 2007; Rubia et al., 2006). However, it should be noted that the functionality of the different regions is mediated more by the type of cognitive information received, than the specific location of the region (Fuster, 2001). This is in part due to the extensive connections between the PFC and other cortical regions along with the extensive feedback loops integrated throughout the cortex (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008;
Duncan & Owen, 2000; Luria, 1976; Niendam et al., 2012).

The orbital PFC plays a role in the cellular and neuronal inhibition of other areas of the brain (Fuster, 2001). These areas include, but are not limited to: the basal ganglia, hypothalamus, the remaining cortex, and other components of the PFC (Fuster, 2001). The orbital PFC is also responsible for situational and social actions (Pribram, 1971). In particular, injuries or damage to this area produce an inability to tolerate interference or distraction of any kind (Fuster, 2001). The medial PFC, which includes the ACC, has been linked to general motility, attention and emotion (Fuster, 2001). The medial aspects of the PFC moderate the reactive response of EF, activating during the monitoring and evaluation stages of EF tasks (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns et al., 2004; van Veen, Holroyd, Cohen, Stenger, & Carter, 2004). Those who suffer damage to this area often also lack spontaneity and struggle to initiate movement and speech (Cummings, 1993; Verfaellie & Heilman, 1987). The lateral PFC is responsible for supporting and developing the temporal organization and mediation of behavior, speech and reasoning (Fuster, 2001). In particular, it is involved in the control of planning and undertaking task-relevant goals (Vijayakumar et al., 2014). It has been proposed that by controlling attention and task-related strategies, the lateral aspects of the PFC are responsible for proactive control of EF (Botvinick et al., 1999; Kerns et al., 2004; van Veen et al., 2004). Damage to the lateral PFC manifests in deficits in planning and both spoken and written language (Fuster, 2001).

The lateral PFC can be further divided into two different regions based on the different roles performed by each. Within each of the two hemispheres of the brain, there is the ventrolateral prefrontal cortex (vlPFC) and the dorsolateral prefrontal cortex (dlPFC). The vlPFC has been linked to proactive control and attention (Vijayakumar et al., 2014), while the dlPFC has been commonly associated with the components of EF, in particular visuospatial working memory (Braver et al., 1997; Casey et al., 2005; Goldman-Rakic, 1995; Moriguchi & Hiraki, 2013). The role of the dlPFC has also been associated with a left/right development division, with retrieval requiring the right dlPFC and encoding using the left dlPFC (Fuster, 2001). It has been suggested that the dlPFC plays a role when the tasks required are novel or there is a switch between tasks (Diamond, 2002).

The PFC develops in size, shape and functionality over the course of childhood, through adolescence and into adulthood (Gogtay et al., 2004; Moriguchi & Hiraki, 2013; Shaw et al., 2006; Sowell, Delis, Stiles, & Jernigan, 2001; Sowell, Trauner, Gamst, & Jernigan, 2002; Tsujimoto, 2008). This anatomical and physiological development is associated with changes in white and grey matter due to synaptic plasticity and myelination (Huttenlocher, 1970, 1979, 1990; Huttenlocher & Dabholkar, 1997). Neuroimaging studies have identified that there are also changes in the connections of the different regions of the PFC as the brain matures (Gogtay et al., 2004; Moriguchi & Hiraki, 2013; Shaw et al., 2006; Sowell et al., 2001; Sowell et al., 2002; Tsujimoto, 2008). These anatomical and physiological changes run in parallel and are linked with the age-related development of EF.

**Chronological Development of Cognitive Functioning**

The three elements of EF have been shown to improve with age, albeit with slightly different trajectories (Karbach & Schubert, 2013; Karbach & Unger, 2014; Titz & Karbach, 2014). The following section maps the trajectory of the PFC anatomy and
physiology, with the age brackets and descriptions of cognitive development of the four Piagetian stages.

**Birth to two years of age**

The first stage of development outlined by Piaget is the Sensorimotor stage between birth and age 2. As mentioned previously, this stage tends to be identifiable by the child’s inability to separate thoughts from action. As the child moves through this stage, however, they begin to develop object permanence. There is a direct link between EF at this age and the maturation of the PFC. Multichannel electroencephalography studies show that PFC is activated in both the A not B Task and the Object Retrieval Task (Fox & Bell, 1990). This is also supported by evidence showing that individuals with lesions in this region are unable to perform either of these tasks (Diamond, 1991; Diamond & Goldman-Rakic, 1985). However, the strong developmental link between EF and the anatomical structure of the brain in school age children has not been as conclusively modeled in younger children. This is because of the lack of functional neuroimaging correlating activation of the PFC during EF tasks when studying young children. The vast majority of studies using fMRI or PET techniques have focused on children over the age of 7 years of age (Tsujimoto, 2008). The introduction of portable EEG has allowed greater opportunity to increase EEG usage to test the role of the brain in respect of the developmental hypothesis (Trainor, 2012).

Using data from post mortem studies, anatomical changes in the PFC have been linked to changes in EF and cognitive development in this age group. It is at this stage that the brain is forming its largest number of new connections between neurons and the brain increases to its absolute size (Selemon, 2013). Between 7 and 12 months of age dramatic synaptogenesis occurs in the brain. This timing is consistent with the development of observable improvements in shifting and inhibition as measured by the EF tasks. Specifically, the dendritic synaptic connections of the layer III pyramidal cell in the dlPFC lengthen and reach adult connection length (Koenderink, Uylings, & Mrzljak, 1994). The length of the synaptic connections continues to remain constant until at least 27 years of age (A. Diamond, 2002). Compared to the rest of the brain, the PFC undergoes delayed development with the dendritic synaptic connections growing to only half of the adult level at age 2 years (Koenderink et al., 1994; Petanjek, Judaš, Kostović, & Uylings, 2008; Schade & Van Groenigen, 1961).

The brain also increases in size during the early stages of development. From birth to 2 years of age, frontal areas of the brain, including the PFC increase in area quickly (Dempster, 1992). One reason for this is the increase in the cell body size of the neurons in the PFC, particularly between 7.5 and 12 months (Koenderink et al., 1994). The cells in the PFC are also undergoing neurochemical change as they develop. Neurotransmitter levels, in particular dopamine (Brozoski, Brown, Rosvold, & Goldman, 1979; Mac Brown & Goldman, 1977) and acetylcholine (Kostović, 1990; Kostović, Škavić, & Strinović, 1988) appear to change in the PFC relative to the rest of the brain during this time. By 12 months the glucose metabolism in the PFC has also reached adult levels (Chugani & Phelps, 1986; Chugani, Phelps, & Mazziotta, 1987). Together these findings suggest increased cellular activity in the PFC.

There have been a number of studies that have linked attention at an early age with EF outcomes later in life. Manifesting from approximately 4 to 6 months of age, it is believed to underpin the child’s ability to shift between objects and representations.
(Rothbart, Ellis, Rosario Rueda, & Posner, 2003). There are age-related increases in the length and frequency of attention as a child moves from early childhood to school age (Lansink, Mintz, & Richards, 2000; Richards, 1989; Richards & Casey, 1991). Espy and Bull (2005) observed that performance outcomes on attention tasks were linked to the difference in young children’s working memory span. It has also been seen that differences in attention during early childhood predict the ability to inhibit responses later in childhood (Sethi, Mischel, Aber, Shoda, & Rodriguez, 2000). Shifting has also been directly linked to attention of children between the ages of 12 months to 4 years old (Kirkham, Cruess, & Diamond, 2003; Thelen, Schöner, Scheier, & Smith, 2001; Zelazo et al., 2003).

Two to seven years of age

All three aspects of EF appear to have large age-related change or a hinge point from 3 to 5 years of age (Best et al., 2011). These changes in EF correspond with movement of the child in the Pre-Operational stage of Piaget’s cognitive development. Piaget himself noted that prior to 3-4 years of age children will fail tests of liquid conservation when comparing the volume of different shaped glasses. Yet when the child is 5 years of age, the majority can complete this task. Neo-Piagetian theorists have also adjusted Piaget’s developmental timeline, creating transitions between their stages of development around 5 years of age (Piaget & Cook, 1953). The transition between Case’s (1985) Inter-relational and Dimensional stage and Fischer’s (1985) Single Representations and Representational Mapping stages occurs between ages 4 and 5 years. This change in Neo-Piagetian developmental stages appears to be analogous with the observed changes in EF lending weight to an association between the two.

Inhibition appears to develop first at a marginally earlier age than shifting and updating. The vast majority of studies suggest that the period of growth for inhibition occurs from around 2 years of age through to 5 years of age, with the child inhibiting for increasing periods of time. The study by Carlson (2005) saw a dramatic shift in the ability of children to suppress eating treats between the ages of 2 and 3. In this study, 50 per cent of 2 year olds were able to hold off eating the treat for 20 seconds (Carlson, 2005). However, 3 year olds were able to fight the urge for 1 minute, 85 per cent of the time (Carlson, 2005).

Response accuracy and latency have been shown to improve in this age group when tested using the Stroop-like Day-Night Task and the Black-White Task. They report an increase in both accuracy and delay time for children between 3-5 years of age (Carlson & Moses, 2001). For the Day-Night task, participants are required to suppress their common response to the stimuli and state the opposite; for example, to say day when a moon is shown and to say night when a sun is shown (Diamond, 2002). Although there has been continuous age-related growth measured in this task, there appears to be a hinge point at 4 years of age. Children younger than 4 years of age find the task very difficult while those older than 4 years find it very easy (Diamond, 2002). This hinge point does appear to be part of a developmental growth trajectory though, with improvements occurring with each year (Diamond, 2002).

Studies using card sorting tasks as the basis for measurement have confirmed rapid developments in cognitive shifting as well as inhibition between 2 and 7 years of age (Kirkham et al., 2003; Moriguchi, Kanda, Ishiguro, & Itakura, 2010; Zelazo, Frye, & Rapus, 1996). The first or pre-switch stage of the task requires participants to sort cards with different images on them by one set of
criteria, for example to sort by the color of the object appearing on the card. The second or post switch stage requires the participants to then sort the cards by a different criterion, for example to sort by the shape of the object appearing. Sorting errors arise when the participants focus on what had been originally relevant, therefore unable to overcome what is deemed “attentional inertia” (Diamond, 2002, p. 481). When using the Dimensional Change Card Sort (DCCS) task, it was observed that there is an age-related change in ability that occurs during this period with a difference in the child’s ability to perform the post-switch phase (Kirkham et al., 2003; Moriguchi et al., 2010; Zelazo et al., 1996). Despite being able to perform the pre-switch phase correctly, children under the age of 4 or 5 are unable to complete the post-switch phase unassisted (Moriguchi & Hiraki, 2013; Zelazo et al., 1996). It should be noted that despite being unable to sort by the new criteria, 3-year-old children are able to state the new rules that have been applied (Zelazo et al., 1996). This behavior is very similar to a person with damage to the PFC (Luria, 1964; Milner, 1964).

Dramatic observable changes can also be seen in updating during this period of growth and development (Alloway, Gathercole, Willis, & Adams, 2004; Gathercole, 1998). Initially, a developmental spurt is observed from 15 months of age until 30 months (Diamond, Prevor, Callender, & Druin, 1997). Like the two previous aspects of EF, there are also large changes in updating ability occurring between the ages of 3-5, tailing off toward the age of 7. Using the noisy book task, Hughes (1998) observed age-related growth in updating around 3 to 4 years of age. During the noisy book test, children press a button that makes various animal noises and are required to repeat different noise sequences (Garon, Bryson, & Smith, 2008). This increase in updating ability has also been supported by an apparent increase in the number of items that a child can remember in order, from 4 to 6 years of age (Hongwanishkul, Happaney, Lee, & Zelazo, 2005), and backwards, from 1.58 to 2.88 items (Carlson, 2005; Carlson, Moses, & Breton, 2002). Luciana and Nelson (1998) found that 4 year-old children performed worse in three and four item searches in the self-ordering searching updating task in comparison to 7 and 8-year-old children. This was also the case for the six-item search, where again the 7 and 8 year-old children outperformed younger children (Luciana & Nelson, 1998). It should be noted that due to the complexity of updating tasks, most studies using complex updating or working memory tests do not examine children under the age of 3 and so there is little data available for this age group.

Between the ages of 2 and 7 there are changes to the underlying anatomical structures and physiological responses in the brain, which have been directly linked to changes in EF. Using functional magnetic resonance imaging (fMRI) studies, the timeline of development of the different EF components has become clearer and have begun to link particular areas of the brain to the different EF components. Moriguchi and Hiraki (2013) examined 5-year-old children and adults during a Dimensional Change Card Sort (DCCS) task – similar to a WCST. Using fMRI, they were able to identify a difference in the regions of the brain activated during the test between adults and children. In particular, they saw that in adults there was greater activation in the left inferior PFC compared with activation in the right inferior PFC in 5 year olds (Moriguchi & Hiraki, 2013). They were also able to identify that the activation of the right inferior PFC in 5 year olds only occurs when they completed the task perfectly, with no activation occurring during errors (Moriguchi & Hiraki, 2013).
In addition, studies using fMRI, EEG, near infrared spectroscopy (NIRS) and Positron Emission Topography (PET) have linked inhibition occurring during the Go/No Go Task to activation of the PFC (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey et al., 1997; Liddle, Kiehl, & Smith, 2001; Moriguchi & Hiraki, 2013). In particular, these studies have indicated that the vlPFC and the dlPFC appear to be activated during these inhibition tasks (Casey et al., 1997; Liddle et al., 2001). These areas of the PFC were also activated when the individual was refocusing attention or shifting between tasks (Fuster, 2001). This is consistent with the behavioural findings that adults with damage to these areas of the PFC show similar results to children before the age of 3 (A. Diamond, 2002).

The anatomy of the PFC is also dramatically changing during the early years of a child’s life. At ages 2 and 6 there are dramatic physical changes to the structure of the brain with increased folding or cortical fissuration occurring (Dempster, 1992). The anatomical change is associated with refinements in the control of behavior and subsequent refinement of connections with other areas of the brain (Rourke, 1983). The PFC does not undergo the same amount of growth in grey matter from 4 years of age onwards as it does before the age of 2 (Dempster, 1992). The grey matter, or the size and density of the neuron cell bodies, continues to develop during early childhood and into adolescence (Gogtay et al., 2004). In the PFC, grey matter reaches its maximum density around age 3 (Huttenlocher & Dabholkar, 1997). However, it is during this period of development that the brain begins to undergo synaptic pruning. The density of synaptic connections in the PFC drops from 55 per cent higher than adult levels at the age of 2 to just 10 per cent above adult levels by age 7 (Huttenlocher, 1990). This is particularly prevalent in the dlPFC (Huttenlocher, 1990).

Changes in white matter, or volume and density of myelinated axons increase during this stage. The process of myelination begins at this age leading to an increase in white matter volume (Mrzljak, Uylings, Van Eden, & Judáš, 1991). The density also continues to increase in the dlPFC as the dendritic tree of layer III pyramidal cells rapidly expand between ages 2 to 5 (Huttenlocher, 1979).

The Pre-Operational stage defined by Piaget exists between the ages of 2 and 7, however, he did note that there were dramatic changes observed in children between ages 3 and 5. An observable change around this age can also be detected when measuring EF and its components. Shifting, inhibition and updating tasks that were too complex for children under the ages of 5 subsequently become manageable and could be completed after the age of 5. This evidence matches the change in EF with the anatomical changes that are concurrently occurring in the PFC.

During this period, there is an increase in the volume of grey and white matter. However, it is at this period that the density of grey matter reaches its peak. These changes have not only been supported by post-mortem studies but they have also been supported by increases in activation of the PFC, seen using functional neuroimaging (Fuster, 2002; Shaw et al., 2006; Shaw et al., 2008).

7 to 11 Years of Age

The Concrete Operational stage of Piagetian development occurs between ages 7 and 11. During this stage the child has developed the principle of conservation and begins to apply logic through steps and stages (Piaget & Cook, 1953; Piaget & Inhelder, 1969; Piaget, Inhelder & Inhelder, 1973). In particular, the child’s thinking becomes more flexible as he or she is able to simultaneously combine perspectives, breaking them down into different approaches and ordering them. Piaget used the conservation test and the class inclusion task as indicators of the
child’s development of operators and subsequent progression through the various stages (Piaget & Inhelder, 1958). Participants completing these tasks move steadily towards adult level as they get older, however there appears to be a tipping point (around 10) at which the vast majority of the participants can complete the task at adult levels (Brainerd, 1973; Brainerd & Kaszor, 1974; Winer, 1980). During this stage, participants improve in speed and accuracy, in part, as a result of developing strategies to apply to the different tasks (Diamond 2002). The timing of the change in development appears to occur concurrently and has been associated with improvements in shifting, updating and inhibition.

This steady and maintained growth in EF matches the simultaneous anatomical changes of the PFC (Diamond, 2002; Giedd et al., 1999; Huttenlocher, 1970). Both grey and white matter increase in volume during this stage (Giedd et al., 1999; Huttenlocher, 1990). The development of grey matter in the PFC has been mapped and follows an inverted U-shaped trajectory (Shaw et al., 2006; Shaw et al., 2008). Giedd et al. (1999) found that the grey matter reached its maximum volume in the PFC at 11 years of age in females and at 12 years of age for males. From this point onwards, the level of synaptic connection reduces through adolescence into early adulthood (Huttenlocher, 1979; Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). The anatomical changes in the PFC, in particular the dIPFC, are delayed when compared to the rest of the brain, which has already begun to undergo reductions in grey matter density due to synaptic pruning which commences much earlier (Gogtay et al., 2004). The development of white matter in the PFC is also delayed in comparison to the rest of the brain as myelination does not reach adult level until late adolescence (Giedd et al., 1999; Huttenlocher, 1970). The increase of white matter occurs during this period of development in a linear manner from 4 to 13 years of age (Giedd et al., 1999).

During the Concrete Operational stage (as with anatomy and physiology of the PFC) all aspects of EF continue to develop and move toward adult levels. Both inhibition and shifting abilities appear to improve along a linear trajectory, reaching adult levels around 11 years of age (Huizinga & van der Molen, 2007). However, updating ability continues to improve into adolescence, reaching maturity around 15 years of age (Huizinga et al., 2006).

Inhibition appears to develop steadily during the ages of 7 and 11 (Klenberg, Korkman, & Lahti-Nuuttila, 2001), with a stronger improvement earlier in the stage (Romine & Reynolds, 2005). Huizinga et al. (2006) showed that children reached an adult level of inhibition at 11 years of age, and Klimkeit, Mattingley, Sheppard, Farrow, and Bradshaw (2004) found that 8 year olds were far more likely to be unable to inhibit the distractor than children of 10 and 12 years (Klimkeit et al., 2004). These results are consistent with previous studies that suggest adult capabilities are reached at 11 years (Bedard et al., 2002; Ridderinkhof & Molen, 1995; van den Wildenberg & van der Molen, 2004; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). Yet it should be noted that Huizinga et al. (2006) also found that there were slight improvements in Stroop-like Inhibition Tests all the way through to 21 years of age, supporting findings that inhibition may improve into adulthood (Leon-Carrion, Garcia-Orza, & Perez-Santamaria, 2004).

As inhibition improves to adult levels, the regions of the PFC and brain activated will change with age. Liston et al. (2006) found that as the child ages, there is an increase in the connections between the PFC and striatum. In particular, they identified a correlation between the activation of the
frontostriatal pathway and the age-changes on the Go/No Go Tasks (Huizinga et al., 2006). EEG based studies of the Go/No go task have also suggested that as a child develops through to adolescence, synaptic pruning modifies connectivity associated cellular inhibition (Lamm, Zelazo, & Lewis, 2006). Functional magnetic resonance imaging studies have also indicated a change in the recruitment of PFC areas as the child ages; there is an increased activation of the ventral frontal region that is positively correlated with performance on a Go/No Go Task (Durston et al., 2006; Durston et al., 2002).

Shifting ability also increases steadily, reaching adult levels at the end of the Concrete Operational age bracket. Although shifting ability does not completely consolidate by 11 years of age, this age is the start of transition to the adult level of functioning (Miles, Morgan, Milne, & Morris, 1996; Wilson, Scott, & Power, 1987). This finding has also been replicated on a visual shifting task (Meiran, 1996), where 80 per cent of 11 year olds were at adult levels for the post switch trials. The response time of 7 and 11 year olds were significantly greater than for 15 year olds, who performed at adult levels (Huizinga et al., 2006). However, this same research group found that despite the change in response time, the accuracy of the task began to reach adult levels at 11 years (Huizinga et al., 2006).

As with the two other components of EF, updating continues to steadily develop in childhood through to adolescence, moving closer and closer to adult levels. However, unlike shifting and inhibition, updating does not reach adult levels during the Concrete Operational stage (Gathercole, Pickering, Ambridge, & Wearing, 2004). Results on the WCST indicate that children make the same number of errors as adults at age 11, however, their ability to complete an increasing number of categories continues well into adolescence (Chelune & Thompson, 1987; Welsh, Pennington, & Groisser, 1991). When analyzing the result for the WCST, Huizinga and van der Molen (2007) report that for children under 11, simple inhibition and shifting tasks could be used as predictors of the child’s results. However, as the child moved to adolescence, updating became the single predictive factor for ages 11, 15 and 21 (Huizinga & van der Molen, 2007). Based on this relationship, the WCST is now used as an indicator of updating for children over 11 years of age.

This pattern of development has also been seen using simpler measures of updating. During the Concrete Operational stage, the number of items that can be held by the child increases (Dempster, 1992). Both the forward and backwards digit spans increase over this time, with the latter increasing more than five-fold (Dempster, 1992). There is also improvement seen in Visuospatial updating tasks (Logie & Pearson, 1997). Using a task based on maintenance of a sequential pattern of recognition, Logie and Pearson (1997) found that children of 7 and 8 performed better than those below 7 years of age.

The age-related improvements in updating tasks appear to be directly linked to an increase in the PFC. Using neuroimaging of the brain during the n-back test, Kwon, Reiss, and Menon (2002) found that a linear relationship existed between the size of the lateral PFC and the test result of participants between the ages of 7 and 22. As the child ages, there also appears to be a separation of the neural circuits used in inhibition and updating (Tsujimoto, 2008). The commonality between these systems appears to begin separating between the ages of 8 and 9 years (Tsujimoto, 2008). During these years, the inhibitory/excitatory cellular networks in the PFC continue to be modified as a result of synaptic plasticity (Selemon, 2013). Inhibitory inter-neurons responsible
for suppressing activity of neurons begin to increase in strength of suppression due to an increase in dopamine firing (Selemon, 2013). The disruption of this mechanism has been linked to deficits in EF and appears to be a factor in the development of conditions in which EF is diminished (Lewis, Hashimoto, & Volk, 2005; O'Donnell, 2011).

During the Concrete Operational stage, there are a number of changes that occur in the brain. The PFC has reached its maximum volume, and the rest of the brain is now beginning to decrease in volume as it moves towards adult levels. This U-shaped trajectory of grey matter volume is contrasted by the linear increase of white matter towards adult levels that occurs at the same time; as with the physiology, the EF components are moving towards their adult levels as well. Children continue to improve on shifting and inhibition tests until the age of 11, at which point they begin to reach adult levels. This is similar to the changes that occur as the child moves through the Concrete Operational stage developing logic and flexibility in cognitive approach.

**Eleven to sixteen years of age into adulthood**

The final stage of Piagetian development, the Formal Operation stage from 11 to 16 years, is characterized by abstract and hypothetical thought (Piaget & Cook, 1953; Piaget & Inhelder, 1969; Piaget, Inhelder & Inhelder, 1973). During this stage, children move through to perfect formal thought and reflective intelligence as they are able to consider different perspectives and alternatives (Piaget, 1950; Piaget & Inhelder, 1958). In particular, Piaget and Inhelder (1958) observed how children in this age group had a greater understanding of action and reaction, pre-emptively considering all possible combinations and outcomes while understanding the relationship between the aspects of a situation (Helmore, 2014). The development of these abilities is necessary for the child to finally reach adulthood.

Neuroimaging studies (Casey et al., 2005) have shown that the anatomical and physiological development of PFC areas during this stage begin to reach maturity and form adult-like networks. Scherf, Sweeney, and Luna (2006) have shown that as the child moves into adolescence, they begin to activate more of the right dlPFC and incorporate usage of the ACC when completing EF tasks. This continues into adulthood as Rubia et al. (2006) have shown that as an individual ages, they will recruit more of their inferior frontal lobes, in combination with the ACC. Between 11 and 16 years of age, the PFC concludes its large anatomical changes. As mentioned above, the volume of white matter develops linearly in this period. This increase in white matter occurs despite the reduction in synapses that occurs during late childhood and adolescence (Huttenlocher & Dabholkar, 1997). This sustained development is due to the continuation of myelination of the axons within the PFC that remain after synaptic pruning. The volume of grey matter follows an inverted U-shaped trajectory with the peak at 11-12 years of age (Shaw et al., 2006; Shaw et al., 2008). Grey matter then reduces in volume, with the most dramatic change occurring in the dorsal frontal and parietal cortices (Jernigan, Trauner, Hesselink, & Tallal, 1991; Sowell, Thompson, Holmes, Batth, et al., 1999). Layer III pyramidal cells in dlPFC reach adult levels at 16 years of age, corresponding with the end of the Formal Operation stage. The reduction in grey matter has been linked to cognitive improvements, in particular the ability to accurately remember words—which is an element of updating (Sowell et al., 2001).

Functional neuroimaging studies have shown that there is a relationship between the reduction of cortical volume during
adolescent years and performance on updating tasks. Tamnes et al. (2013) found that the degree of improvement on a Keep-track Test was associated with a reduction in cortical thickness of bilateral PFC. These changes were independent of other factors such as age, gender and intelligence (Tamnes et al., 2013). Improvements in inhibition response times and accuracy have also been linked to cortical thinning of the right vLPFC and the ACC during this period (Vijayakumar et al., 2014). The development of grey matter in the PFC has been directly linked to intelligence and improved cognitive performance, especially in updating (Sowell et al., 2001). The link appeared to be between a thinning of the grey matter in adolescence after a period of thickening during childhood (Shaw et al., 2006).

As mentioned above, it appears that inhibition reaches adult levels around 11-12 (Bedard et al., 2002; Bunge et al., 2002; Durston et al., 2002; Ridderinkhof & Molen, 1995; van den Wildenberg & van der Molen, 2004). It should be noted, however, that there are a few studies that suggest that inhibition may reach adult level after 11-12 years of age (Welsh, Satterlee-Cartmell, & Stine, 1999). For example, Huizinga et al. (2006) measured increased improvement in the Stop-signal Task and the Eriksen Flankers Task until age 15, and on a Stroop-like Task until age 21. Despite this, the majority of the literature proposes that inhibition does not change or develop during the Formal operation stage, as it has already reached adult levels (Bedard et al., 2002; Bunge et al., 2002; Durston et al., 2002; Ridderinkhof & Molen, 1995; van den Wildenberg & van der Molen, 2004).

Unlike inhibition, the literature highlights minor improvements and refinement of shifting to reach adult levels during the Formal Operation stage (Anderson, 2001; Huizinga et al., 2006; Huizinga & van der Molen, 2007; Somsen, 2007). Huizinga et al. (2006) found that the response time during a shifting task does not reach adult levels until age 15. This was also seen by Gathercole et al. (2004) who observed both a decrease in reaction time and an increase in accuracy rate up until age 15.

As inhibition and shifting reach adult levels, the role those factors play in influencing an EF task when compared with updating appears to change. Participants completing the WCST did not reach adult levels until 15 years of age (Chelune & Baer, 1986; Chelune & Thompson, 1987; Levin et al., 1991; Welsh et al., 1991). Despite the variability of difficulty of updating tasks, the majority of studies suggest that 15 years old is the adult level, with latent levels of maturation after that age associated with the task form (Gathercole et al., 2004).

Piagetian cognitive development theory states that the Formal Operation stage is the entry point into adulthood and adult cognitive abilities. However, as the model of cognitive development has been adapted by other neo-Piagetian theorists, the trajectory has continued to be mapped into late adolescence and early adulthood (Case, 1985; Demetriou & Efklides, 1987; Fischer, 1980). This may reflect the continued physiological and anatomical development of the brain after the age of 16 years. A number of studies have suggested that synaptic plasticity, specifically synaptic pruning, continues after 16 through to early adulthood (Huttenlocher, 1990; Kolb & Gibb, 2011; Selemon, 2013). The protracted adaptation and development of the PFC and the brain is due to Hebbian principles and increases efficiency by strengthening the commonly used neural connections.

There also appears to be a change in the cognitive response to EF tasks as the individual ages. Despite reaching adult levels of accuracy and reaction time at around 11, it appears that the neural
pathways and correlates used to complete the Stroop Test continue to develop well into adulthood (Andrews-Hanna et al., 2011; Comalli Jr, Wapner, & Werner, 1962; Yurgelun-Todd, 2007). As individuals move into adulthood, there is an age-associated increase in the use of the right lateral PFC when completing EF tasks (Marsh et al., 2006).

The Formal Operation stage is where children move to have adult levels of cognition. Functional neuroimaging has shown that the older the children get, the more they use their lateral PFC when solving EF tasks and problems. By age 16 years the PFC has become fully formed, as synaptic plasticity has reduced the grey matter to that comparable with an adult volume. During this time, the white matter is also moving closer to adult level, increasing linearly until the early 20s. The components of EF—shifting, inhibition and updating—have all now reached adult level, this matches the Piagetian description of children at the end of this final stage.

A neurological and psychological basis for Piagetian cognitive development

This literature review illustrates that changes in brain development are aligned with Piagetian stages and, indeed, can help underpin and confirm Piaget’s theories. By drawing attention to the similarity of the three separate developmental measures—anatomical and physiological changes in the brain, EF improvements and Piagetian developmental stages—commonality between the three fields of research is highlighted. In particular, it demonstrates that a relationship exists between the biological changes associated with age and growth, and the subsequent manifestation of observable changes in the cognition of the child.

As summarized in Table 1, when EF and PFC changes are mapped in conjunction with the Piagetian stages, a clear cognitive developmental trajectory from birth through to adulthood begins to emerge. From birth through to 2 years of age, the child is beginning to develop their initial cognitive abilities. Although limited effective tests exist for this initial stage of development, from 12 months of age children begin to show cognitive ability on both Piagetian and EF measures. The first component of EF, inhibition, manifests in the child’s behavior and continues to grow steadily from 12 months of age until around 3 years of age. This spike in EF occurs at the same time as dendritic connections in the PFC begin to reach adult lengths. It appears that the development of cognition in this early stage occurs as a result of increasing size, density and connectivity of the PFC.

Piaget indicated that during the Pre-Operational stage there was a change in the observable behavior of children between ages 3 and 5. This age is at the same hinge point that has been observed in changes in EF. Shifting, inhibition and updating tasks that were too complex for children under the ages of 5 subsequently become manageable and are completed after the age of 5. This stage of development is also the period in which the PFC begins to increase in its volume of grey and white matter, with the density of grey matter reaching its peak. Functional neuroimaging has also shown an increase in activation of the PFC during this hinge point (Moriguchi & Hiraki, 2013).

Once reaching the age of 7 or the Concrete Operational stage, the rate of development begins to follow a smooth growth curve. Children continue to improve on shifting and inhibition tests until the age of 11, at which point they begin to reach adult levels. This period of steady EF growth is also the time that grey matter in the PFC reaches its maximum volume and begins to decrease
towards adult levels (Shaw et al., 2006; Shaw et al., 2008). This is occurring at the same time as the amount of white matter is increasing in a linear fashion towards adult levels (Giedd et al., 1999; Huttenlocher, 1990).

### Table 1

*Summary of key changes in executive function and brain development matched to Piagetian stages*

<table>
<thead>
<tr>
<th>Piagetian Stage</th>
<th>Cognitive (EF) Development</th>
<th>Brain (PFC) Development</th>
<th>Key References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Operational 7-11 Years</td>
<td>Inhibition and shifting reach adult levels at 11 years of age.</td>
<td>Volume of grey matter has reached maximum level and begins to decrease. White matter continues to increase in volume.</td>
<td>Giedd et al. (1999) Huttenlocher (1970) Huizinga et al. (2006)</td>
</tr>
</tbody>
</table>
By the end of the final stage of cognitive development, children have reached the basic adult level of cognition. The final development towards adult cognitive abilities occurs at the same time as children are reaching adult levels of updating proficiency. The older the child gets, the more he or she uses their lateral PFC when solving EF tasks and problems, which has now become fully formed. Synaptic plasticity, which has been occurring during childhood, reduces as the grey matter reaches adult volume. Simultaneously, white matter in the PFC reaches its adult level at the end of this stage.

There is a close relationship between the anatomical and physiological development of the PFC and the measurable changes in EF over time. This relationship has been observed both qualitatively and quantitatively. What is of particular interest is the timing of the changes and their parallels with the Piagetian and neo-Piagetian cognitive development trajectories. The absence of comparison in the literature between these elements is surprising given the similarity of the tests and tasks that measure the Piagetian cognitive levels and the EF tasks. Some tests, such as the A not B Test, are used for measuring both EF and Piagetian development, while other tasks measure the same fundamental EF component with slightly different methodologies.

Another similarity between Piagetian development and EF is in the language and focus of the observation. The operators that Piaget states come into effect during the Concrete Operational and Formal Operational stage are similar in definition to the updating aspect of EF. This similarity in definition is also seen when Pascual-Leone describes the concept of mental power and interrupt operators (1970). There is a commonality in language used for mental power and updating, and interrupt operator with inhibition. It appears that as the neo-Piagetian theorists increased the complexity of their models, they inadvertently talked about concepts such as plasticity and neural connectively without explicitly stating or identifying the biological basis for these phenomena. For example, a parallel exists between Fischer’s description of environmental contribution and experience-dependent plasticity (1980). It can therefore be theorized that what the neo-Piagetian theorists were talking about was the development of EF over the life of the child. This provides a new context and a new framework for educators, physiologists and neuroscientists to examine cognitive development.

Limitations

Despite the apparent parallel relationship between the chronological development of EF, the PFC and the stages outlined by Piaget, there are a number of limitations that exist in this examination. First, EF has a large variability in definition (Jurado & Rosselli, 2007) and the many components can be difficult to measure accurately (Miyake et al., 2000). This study has used Miyake et al. (2000) “a latent variable” approach which is based on three major dimensions of EF. As we learn more about the dimensions and their changes over time, further clarification of their role in achievement is likely to occur.

Second, although this review points to the existence of an underlying biological basis for cognitive development, this should serve simply as a guideline and an area for future studies. The literature clearly states that developmental trajectories can be different depending on the context of the individual. For example, bilingual children appear to have an accelerated development of EF when compared to monolingual children, and this difference appears to extend from infancy (Kovács & Mehler, 2009)) through to adulthood (Bialystok & Shapero, 2005).
Environments high in enrichment, such as bilingualism, have also been linked to increases in size, connectivity and complexity of the brain (Baroncelli et al., 2010). The opposite effect has been observed in individuals who are raised in environments where there is a deficit of food, shelter, education and enrichment or where drug, stress, disease and abuse are present (Hackman, Farah, & Meaney, 2010). A recent study has shown that the anatomy, physiology and, subsequently, the EF of children who grow up in low socioeconomic environments are smaller than those who grow up in affluent communities (Hackman et al., 2010).

Although a relationship has been identified between EF, the PFC and Piagetian development, care needs to be taken when tying specific cognitive abilities directly to distinct ages. There is considerable variability across individuals in brain development and subsequently cognitive ability. The trajectory outlined here should be used as a guide by which to explore the most common developmental pattern. Further, the impacts of interventions, such as pre-school, schooling and parental involvement have not been considered in this examination. These early childhood factors may have an impact on developmental trajectory of the individual child. For example, Shayer (2003) claimed that the average age of a student in the United Kingdom moving into the Formal Operation stage has shifted closer towards 15 years of age, compared to 11 years of age a generation ago. He argued that this is because schools overemphasize surface rather than formal thinking—whether this is the reason or not, care needs to be taken when generalizing the age changes to all students.

Finally, this literature review does not explore the different modalities and domains associated with the tasks. The different cognitive development trajectories have been seen to vary based on the modality of the tasks used. For example, a visual updating task, such as non-verbal face task will develop more quickly than an arithmetic manipulation updating task such as the Add 1 or Add 3 Task. This is due the underlying task specific literacy involved in completing this task. Segregation and isolation of the modalities is an issue of both neo-Piagetian tests and EF tasks and as such, resolving this issue was outside the scope of this review.

**Conclusion and future directions**

Piaget was among the first psychologists to mainstream the concept of discrete and staged cognitive development. With his theory, educators began to have a scaffold by which to examine the underlying mechanisms that allow learning to take place. Despite the large-scale adoption of Piaget’s theory in psychology and education, and the subsequent adjustment of his developmental timeline within the neo-Piagetian development theories, his theories have lost favor in recent times. In more recent years, two schools of thought have dominated cognitive development theory. The first encompasses those who assume that development is due to the increase of processing speed or resources that increase over time (Bjorklund & Harnishfeger, 1995; Case, 1985), and the second asserts that as the child develops, the means by which the individual deals with information changes (Fischer, 1980; Piaget & Cook, 1953; Siegler, 2013). What this review exposes is that both theories may align with changes based on the development of the anatomy and physiology of the brain—in particular the PFC and associated connections. Although these changes are primarily cellular, it is important to recognize that they may be influenced by the environment in which the individual is raised.

This finding highlights a range of future investigations. First, the relationship be-
between EF, the PFC and Piagetian development needs to be examined in greater detail and quantified. A longitudinal study that examines the change in the participant’s EF, PFC and academic achievement over the course of a number of years would provide insight into this developmental pattern. As part of any future longitudinal study, there should be a consistent examination of the three different EF components. Such studies would allow for a more accurate delineation of the developmental trajectories over the life of the participant, and matching these different trajectories with the changes in academic achievement would allow for a greater understanding of the influence these components have on academic ability. This needs to be done across different modalities and tasks types. The longitudinal study should, where possible, include functional neuroimaging of the brain during these EF tasks and academic tests in order to correlate the changes with the underlying brain structure and function.

Second, another area for future exploration is to examine the relationship between genetics and the developmental progression of EF. Studies have indicated there is a correlation of 0.75 between the EF and heritability (Miyake & Friedman, 2012). If a genetic component is found, a further question to explore is if this genetic component is different in individuals with disabilities that affect cognitive development.

Although questions still remain over the exact pattern of the development, it appears that the chronological nature of this cognitive development is matched by anatomical and physiological changes in the brain. This discovery is exciting as it allows for an opportunity to accurately measure and diagnose the underlying ability that influences academic achievement. By mapping a developmental trajectory for EF, it may be possible to develop a diagnostic tool to review a student’s developmental status. With this information, teachers would be better equipped to accurately identify the needs of the students and subsequently improve their learning through targeted teaching. This targeted teaching should involve the appropriate academic learning and domains and not focus on the EF skills, as currently there has been no data to indicate that teaching EF improves academic outcomes. The creation of a diagnostic tool that is derived from the collective evidence and knowledge gained from the fields of neuroscience, psychology and education, concerning the development of the brain and executive function, may enhance our resources to improve the day to day outcomes of students. As stated by Shayer (2003, p. 481):

*If you cannot assess the range of mental levels of the children in your class, and simultaneously what is the level of cognitive demand of each of the lesson activities, how can you plan and then execute – in response to the minute by minute response of the pupils – tactics with results in all engaging fruitfully?*
**Figure 1.** Age-related changes in the components of Executive function, Prefrontal cortex grey matter, Prefrontal cortex white matter matched with Piagetian stages of cognitive development. Data for the graph has been sourced from other studies, modified and standardized. As such, components of Executive function begin at Seven years of age due to methodology of original study. 1. Huttenlocher & Dabholkar, (1997), 2. Giedd et al. (1999), 3. Huizinga et al. (2006)

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