New perspectives on self-control development: Highlighting the role of intentional inhibition

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**A R T I C L E  I N F O**

Available online 27 August 2014

Keywords:
Self-control
Intentional inhibition
Delay discounting
Development

**A B S T R A C T**

The ability to exert self-control over one's thoughts and actions is crucial for successful functioning in daily life. To date, self-control development has been primarily studied from the perspective of externally driven inhibition. In this review, we introduce a new perspective on the development of self-control by highlighting the importance of intentional inhibition. First, we will review the existing behavioral and neuroscientific literature on the development of self-control from the perspective of externally driven inhibition. Next, we will introduce a new framework for studying the development of self-control from the perspective of intentional inhibition. We will discuss several recent studies in this domain, showing that intentional inhibition within cold contexts has an early development, but continues to develop through adolescence in motivational contexts. We conclude that understanding the developmental trajectory of intentional inhibition in cold and motivationally relevant contexts and its underlying mechanisms is an important direction for future research, which has important implications for our understanding of developmental disorders associated with problems in self-control, such as Attention Deficit Hyperactivity Disorder.

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1. Introduction

Self-control can be defined as the ability to exercise control over one's action, thoughts and emotions (Casey & Caudle, 2013). Self-control abilities are crucial for successful functioning in all aspects of human life (e.g. social situations, educational and work environments). The development of self-control is an important aspect of cognitive development through childhood and adolescence (Diamond, 2013), and has far-reaching implications during this important developmental period. That is, self-control is important for learning (e.g. concentrating on the task at hand and not getting distracted by the environment), for making optimal decisions (e.g. healthy food-related or financial decisions), for keeping friendships (e.g. not reacting impulsively and hitting someone, when being teased), and for social skill development (e.g. inhibit the impulse to cut in line) (Diamond, 2013).

At the core of self-control lies the ability to intentionally inhibit one's actions. Intentional inhibition has been defined as a late ‘veto’ mechanism (Filevich, Kühn, & Haggard, 2012; Haggard, 2008). By means of this late ‘veto’ mechanism, one can cancel action execution of an already initiated action at the last possible moment, as given in by an internal thought process (Filevich et al., 2012; Haggard, 2008). Thus, intentional inhibition differs from stimulus- or externally driven inhibition in that it is driven by an internally generated process, rather than an external stimulus which tells you to stop your behavior. To date self-control development has been primarily studied from the perspective of externally driven inhibition (for a review, see Diamond (2013)), yet, intentional inhibition is clearly present in many aspects of children's life, such as when inhibiting the tendency to get up of their chair and walk around in the classroom based on internally set goals, or when trying to finish a tedious task without supervision. In addition, given that intentional inhibition lies at the core of self-control, that is to say, most of our action control is driven by internal motives, problems in intentional inhibition have wide-ranging implications, such as for childhood psychological and psychiatric disorders, such as Attention Deficit Hyperactivity Disorder (ADHD) (Moffitt et al., 2011) or conduct disorder (Fergusson, Boden, & Horwood, 2013).

Therefore, the goal of this review is to describe a new perspective on the development of self-control by highlighting the importance of intentional inhibition and the new advances in studying this domain. As such, we will first review the existing behavioral and neuroscientific literature on the development of self-control,
with a focus on what is currently known about externally guided inhibition. Next, we will describe the distinction between externally and internally guided self-control and introduce a new framework for studying the development of internally guided self-control, drawing on behavioral, psychophysiological and neuroscientific findings. Several recent studies in this domain will be presented. Finally, we will discuss the implications of this new framework for developmental disorders.

2. The development of self-control: externally guided inhibition

The ability to control one’s actions and stop actions when the environment requires one to do so, also referred to as inhibition, is one of the most studied components of self-control development (Diamond, 2013; Zelazo et al., 2003). There are marked improvements in inhibition in infancy (Diamond, 2013), early childhood (Zelazo et al., 2003) and school-aged children (van der Molen, 2000), which has been interpreted as reflecting the protracted development of executive control functions. Executive control is often used as an umbrella term to refer to our ability to control our thoughts and actions in order to attain future goals, and inhibition is a key component of executive control (Diamond, 2013). As such, inhibition is thought to lie at the core of cognitive development (Diamond, 2013).

Most research on the development of inhibition has focused on the development of stimulus-driven inhibition. In these experiments, inhibition is typically preceded by an external stimulus or cue, which signals that one has to stop an already initiated or prepotent action. Research with two experimental paradigms has contributed significantly to our knowledge of the mechanisms underlying stimulus-driven inhibition, namely the stop-signal paradigm and the go/no go paradigm. In the stop-signal paradigm participants are presented with a simple stimulus (e.g. a left or right pointing arrow) to which they have to respond as quickly as possible. On a limited number of trials (i.e. about 25% of all trials) a stop signal (e.g. a loud noise or a color-change of the stimulus) is presented after the stimulus has come online. By varying the delay between presentation of the stimulus and presentation of the stop-signal, it is possible to calculate the Stop Signal Reaction Time (SSRT), that is the time one needs to inhibit an already initiated response (Band, van der Molen, & Logan, 2003; Logan & Cowan, 1984). The go/no go go paradigm also examines the inhibition of prepotent responses (Casey et al., 1997). In this paradigm, participants are presented with a stream of stimuli (e.g. different letters) to which they have to respond by pressing a button. However, one stimulus (e.g. the X) is instructed to be a no go-stimulus, signaling that participants have to withhold responding. This no go-stimulus is presented on a limited numbers of trials (i.e. around 20% of all trials), and when this no go-stimulus is presented participants have to inhibit a prepotent response to the presentation of a new stimulus (Casey et al., 1997). In contrast to the stop-signal paradigm, the go/no go paradigm does not allow for a calculation of the SSRT. Instead, the dependent variable in the go/no go paradigm is the number of false alarms (i.e. the number of times a participant does not inhibit when a no go-stimulus is presented).

Cross-sectional developmental comparison studies using these paradigms have shown that stimulus-driven inhibition has a protracted development (Casey et al., 1997; Cohen et al., 2010; Durston et al., 2002; Rubia, Smith, Taylor, & Brammer, 2007). Studies using the stop-signal paradigm have found that even though children are already able to inhibit, the SSRT continues to become faster across development (between 6 and 30 years of age) (Cohen et al., 2010; Ridderinkhof, Band, & Logan, 1999; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). Furthermore, studies using the go/no go paradigm have shown that even though 6–10 year-old children are already able to inhibit, they are more susceptible to the effects of prepotency of responding (Durston et al., 2002). That is to say, when a no go-trial was preceded by a larger number of go-trials, thereby increasing the prepotency of responding, children experienced more difficulty inhibiting responding to that no go-stimulus (Durston et al., 2002). Taken together, young children are already able to inhibit, but not to the same level as adults and not in a stable level across the full duration of a paradigm (Diamond, 2013; Luna, Padmanabhan, & O’Hearn, 2010). This ability continues to improve across childhood and adolescence, with mature performance levels being reached in early (11 years of age) (Huijinga, Dolan, & van der Molen, 2006) to late adolescence (18 years of age), depending on task-difficulty (Luna et al., 2010).

Neuroscientific studies in adults have shown that a specific network of brain regions is active when participants perform a stop-signal task. This network involves the dorsal and ventral prefrontal cortex (specifically right inferior frontal gyrus (IFG)), the anterior cingulate cortex (ACC)/pre-supplementary motor area (SMA) and parts of the basal ganglia, including the subthalamic nucleus (STN) (see Fig. 1) (Aron & Poldrack, 2006; Ridderinkhof, Forstmann, Wylie, Burle, & van den Wildenberg, 2011; Verbruggen & Logan, 2008). Individual differences analyses have shown that activity in rIFG and STN correlates with SSRT, suggesting that these are core regions for successful response inhibition (Aron, Behrens, Smith, Frank, & Poldrack, 2007; Aron & Poldrack, 2006). In addition, functional and structural network analyses have found that increased connectivity between rIFG and STN is related to successful response inhibition performance (Aron et al., 2007; Forstmann et al., 2012; Jahfari et al., 2011; King et al., 2012).

Compared to adults, children show different activity during externally driven response inhibition. Specifically, some studies have shown that 8–12 year-old children use left lateralized PFC regions whereas adults use right lateralized regions (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002), some studies reported more activity in dorsolateral prefrontal cortex in 8–12 year-old children compared to adults (Velanova, Wheeler, & Luna, 2008), and others reported more activity in ventrolateral PFC in adults than in 6–10 year-old children (Durston et al., 2002). Together, these changes can be characterized as a shift from diffuse to focal activity (Durston et al., 2002). In other words, in childhood, widespread inhibition related activation was observed across lateral prefrontal cortex (Durston et al., 2002; Luna et al., 2010), whereas with increasing age this activation became more focalized to the rIFG (Durston et al., 2002; Luna et al., 2010). These findings are consistent with structural neuroimaging studies showing that regions in the lateral prefrontal cortex are the last to mature in terms of loss of gray matter volume, which is an index of neuronal maturation (Giedd, 2004; Shaw et al., 2008; Sowell et al., 2004), as well as in terms of slowly developing white matter maturation in the prefrontal cortex and its connections (Paus, 2010; Paus et al., 2001).

These findings fit well with studies focusing on other components of executive control which also rely on lateral prefrontal cortex, such as working memory (e.g. Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006; Finn, Sheridan, Kam, Hinshaw, & D’Esposito, 2010; Jolles, Kleibeuker, Rombouts, & Crone, 2011), task switching (e.g. Christakou et al., 2009; Crone, Donohue, Homochil, Wendelken, & Bunge, 2006), and attention (Smith, Halari, Giampetro, Brammer, & Rubia, 2011). These studies also reported that prefrontal cortex activity is developing protractedly in childhood and adolescence, which has been interpreted in terms of increased interactive specialization (i.e., an interactive experience-related process where some regions become less and other regions more involved in the task over time) of brain regions important for...
higher order cognitive processes (Johnson, 2011). In sum, there is substantial evidence that response inhibition, measured by the inhibition of behavior based on external signals, lies at the core of cognitive development (Diamond, 2013), matures slowly across development (Diamond, 2013; Luna et al., 2010), and is associated with immature activity in the prefrontal cortex (Luna et al., 2010).

3. The development of self-control: intentionally guided inhibition

Many of our daily activities involve stopping actions based on internally generated (i.e., intentional) stop signals, rather than explicit external stimuli telling us to stop our actions. Despite the clear importance of the intentional component of inhibition, intentional inhibition has not been often addressed in developmental psychology and developmental cognitive neuroscience. Since intentional inhibition is not preceded by an external stimulus or cue, and does not result in any behavioral output, there are obvious difficulties in studying intentional inhibition. However, the need to inhibit is not constantly signaled by external cues, and therefore, understanding the mechanisms of intentional inhibition is of clear importance.

3.1. How to examine intentional inhibition

A useful framework for studying intentional inhibition is the factorial organization of action control (Filevich et al., 2012). According to this framework both the motivation for action and the motivation for inhibition can be externally or internally guided (see Table 1). Importantly, in daily life, action and inhibition decisions are often based on a combination of external and internal motivations. For instance in our previous example of children having to intentionally inhibit the tendency to get up of their chair and walk around in the classroom, external factors such as teacher expectations also play a role. Within experimental research, internal and external motivations for action and inhibition are separated by the presence or absence of an external cue signaling action or inhibition (Filevich et al., 2012).

Stimulus-driven inhibition involves the externally guided inhibition of both externally and internally guided action. However, as outlined above, traditionally most research has focused on externally guided inhibition of externally guided action. Intentional inhibition on the other hand involves the internally guided inhibition of both externally and internally guided action. When studying intentional inhibition there are three main difficulties (Filevich et al., 2012). First, intentional inhibition does not result in any behavioral output. Thus, on the behavioral level one can only examine whether someone has intentionally inhibited or not. However, concluding that intentional inhibition has happened on the basis of no behavioral output is

Table 1
Factorial organization of action control.

<table>
<thead>
<tr>
<th>Action</th>
<th>Externally guided</th>
<th>Internally guided</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhibition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Externally guided</td>
<td>Stop walking when a green traffic light suddenly turns red.</td>
<td>Stop teasing a classmate when a teacher suddenly appears.</td>
</tr>
<tr>
<td>Internally guided</td>
<td>Resisting the impulse to take another biscuit from the biscuit box standing in front of you.</td>
<td>Resisting the impulse to cut in line.</td>
</tr>
</tbody>
</table>

![Fig. 1.](image-url)
problematic (see the third point). Therefore, psychophysiological and neuroimaging measures are particularly useful in the study of intentional inhibition, since they can help identify the covert processes associated with inhibition. A second difficulty in the study of intentional inhibition is that, intentional inhibition because it is an internal process, which is not triggered by an external stimulus or cue, it cannot be easily manipulated in an experimental task. Third, according to our definition of intentional inhibition, intentional inhibition involves the inhibition of an action. However, at the behavioral level we cannot distinguish between an action that was inhibited and an action that was never prepared. In the latter case, we would speak of early decision not to prepare an action. This process is linked more to action selection than to inhibition (Haggard, 2008). Early decisions not to prepare an action are more likely in paradigms where there is no strong motivation for acting (Filevich et al., 2012). Therefore, paradigms designed to measure intentional inhibition should include a strong motivation or prepotency for acting.

The marble paradigm (see Fig. 2A) is a valuable paradigm to study intentional inhibition, which was first developed by Kühn, Haggard, and Brass (2009). In this paradigm, a white marble is rolling down a ramp. As soon as the marble starts rolling, the marble changes color to green. Participants are instructed to respond to the rolling marble as quickly as possible, in order to prevent the marble from dropping from the ramp and crashing. On a number of trials (around 35%, this differs slightly between experiments), the rolling marble does not change color and remains white. In this case, participants are free to choose to either respond or inhibit. The large proportion of green trials serves two functions. First, the green trials lead to a prepotent tendency for action. Since the green marble trials are rather difficult, participants have to remain focused on the goal of responding quickly to the rolling marble, thus increasing the prepotency of responding. Also, due to the intermixed presentation of green and white trials participants cannot predict when a white trial will be presented. Therefore participants have to be prepared to quickly respond to a green marble during the whole duration of the experiment, leaving the prepotency intact. This is desirable, so that intentional inhibition of action will involve a late brake on an already-prepared action, rather than a decision not to initiate action preparation. As will be shown in the subsequent sections, combining the marble task with heart rate and neuroimaging techniques can provide valuable insights in the processes involved in intentional inhibition.

3.2. Psychophysiological and neural concomitants of intentional inhibition

A useful measure for studying the covert processes underlying intentional inhibition is the study of phasic heart rate changes. Phasic heart rate changes are shown to be a sensitive index of cognitive control processes in general (Crone, Somsen, Van Beek, & Van Der Molen, 2004; Crone et al., 2003; Jennings, Van der Molen, & Debski, 2003), and response activation and inhibition processes in particular (Jennings & van der Molen, 2002; van der Molen, 2000; Van der Veen, Van der Molen, & Jennings, 2000). During preparation and/or anticipation of a speeded response (a go-stimulus in a go/no go or stop-signal paradigm), a pattern of heart rate deceleration is typically observed (Jennings & van der Molen, 2002, 2005; Jennings, van der Molen, Somsen, & Terezis, 1990). This pattern of anticipatory heart rate deceleration is interpreted as indicative of the central inhibition of action representations (Jennings & van der Molen, 2002, 2005). This anticipatory heart rate deceleration is followed by acceleratory recovery when a response is made (Jennings & van der Molen, 2005; Jennings et al., 1990). However, during inhibition, the shift from anticipatory heart rate deceleration to acceleratory recovery is delayed, and heart rate continues to decelerate (Börger & van der Meere, 2000; Jennings & van der Molen, 2005; Jennings, van der Molen, Pelham, Debski, & Hoza, 1997; van der Molen, 2000; Van der Veen et al., 2000). This continued deceleration is implicated to be indicative of midbrain

![Fig. 2](image-url)

**Fig. 2.** (A) Schematic representation of the marble paradigm. See text for details about the paradigm. (B) Percentage of internally guided inhibition choice for children (8–10-year olds), early adolescents (11–12-year olds), and adults (18–26-year olds). (C) Stimulus-locked heart rate changes associated with externally guided action, omission, internally guided action, and internally guided inhibition. IBI 0 refers to the IBI during which the marble started rolling. An increase in IBI difference scores indicates heart rate deceleration, and a decrease in IBI difference scores indicated heart rate acceleration. Note: IBI = Interbeat Interval, the time between two consecutive heart beats in milliseconds.
inhibition of action (Jennings, van der Molen, & Stenger, 2008; Van der Veen et al., 2000).

This measure was applied to study the covert components of intentional inhibition using the marble paradigm (Schel, Windhorst, van der Molen, & Crone, 2013). In this study the following conditions were dissociated: actions on the externally driven green action trials, omissions on the externally driven green action trials, decision to act on the intentional white trials, and decisions to inhibit on the intentional white trials. In line with the literature on externally driven inhibition (Jennings & van der Molen, 2005; Van der Veen et al., 2000), anticipatory heart rate deceleration was observed for all conditions. However, heart rate continued to decelerate in both the intentional action and the intentional inhibition condition, indicative of involvement of a supervisory attentional system in intentional action and inhibition decisions. Importantly, heart rate deceleration was most pronounced during intentional inhibition, indicating that an active inhibitory process was in place. Taken together, in this study it was found that heart rate was sensitive to intentional decisions to act or inhibit (see Fig. 2C) (Schel et al., 2013).

A second method, which is useful for unraveling the covert processes involved in intentional inhibition, is neuroimaging. fMRI studies can generate more specific hypotheses about the underlying mechanisms involved in externally driven and intentional inhibition. The first fMRI study specifically designed to measure intentional inhibition made use of a free choice paradigm involving the internally generated inhibition of internally generated action (Brass & Haggard, 2007). In this paradigm, participants were asked to always prepare and perform a simple action (i.e. a key press) at the time of their choice. Importantly, participants were instructed to withhold this action at the last possible moment on some freely chosen trials. On every trial, including those when their action was inhibited, participants reported the time at which they felt they were about to perform their action. This reported time, also in the absence of action, formed the event modeled in the fMRI analysis. This analysis showed specific activation during intentional inhibition in the dorsal fronto–median cortex (dFMC), a brain region not implicated in stimulus-driven inhibition (see Fig. 1) (Brass & Haggard, 2007). However, the free choice paradigm differs in two aspects from traditional stimulus-driven inhibition experiments, which focus on externally guided inhibition of externally guided action. That is to say, in this free choice paradigm both the decision to act and the decision to inhibit were internally guided, making the interpretation of these results difficult.

In an fMRI study in adults, Kühn et al. (2009) introduced the marble paradigm, which only differs in the internal initiation of inhibition from the traditional stimulus-driven inhibition paradigms. The critical contrast focused on brain regions that were more active during intentional decisions to inhibit compared to intentional decisions to act. This study also showed specific activation in the dFMC during intentional inhibition (Kühn et al., 2009), comparable in location to the study by Brass and Haggard (2007). One question that remained unanswered was the extent to which this activation was dependent on prepotency of responding. To address this question, Schel et al. (2014) used the same task but made a distinction between intentional action and inhibition decisions that were preceded by different numbers of externally driven green action trials, thereby varying the prepotency of responding. Here, it was found that dFMC activation is context specific (Schel et al., 2014). That is, as shown by a parametric analysis, participants showed less dFMC activation during intentional inhibition when there was a strong prepotency for acting (i.e. when the intentional inhibition trial was preceded by a larger number of green action trials). Also the behavioral results showed that participants were less likely to inhibit when there was a strong action prepotency (Schel et al., 2014). A second issue that was addressed in this study was the extent to which there was overlap in activation for externally and internally guided inhibition. Schel et al. (2014) showed that there is considerable overlap in the neural networks involved in intentional and stimulus-driven inhibition. Thus, although intentional inhibition is conceptually different from stimulus-driven inhibition, similar inhibitory networks were involved when inhibition was applied, irrespective of how (intentional or stimulus-driven) inhibition was initiated (Schel et al., 2014).

These results show that, in adults, intentional and externally guided inhibition activate a similar network of regions in lateral prefrontal regions (including rIFG) and ACC/preSMA. However, intentional inhibition also appears to be associated with distinct activation in dFMC, a region that is not involved in stimulus-driven inhibition (Brass & Haggard, 2007; Kühn et al., 2009; Schel et al., 2014). This dFMC region extending to the dorsal ACC is also found to be the main region important for intentional inhibition in a meta-analysis of fMRI studies looking at intentional inhibition (Filevich et al., 2012). Interestingly, although intentional inhibition cannot be easily manipulated because it is not triggered by an external signal or cue, it has been shown that varying the preceding context can influence both the likelihood of intentional inhibition and the level of activation of the dFMC during intentional inhibition (Schel et al., 2014). Thus, the underlying neural mechanisms of intentional inhibition appear to be at least partly distinct from the neural mechanisms underlying externally guided inhibition.

3.3. Development of intentional inhibition

As outlined above, stimulus-driven inhibition appears to have a protracted developmental trajectory (Diamond, 2013; Luna et al., 2010), with mature performance levels being reached in late adolescence (Luna et al., 2010). This protracted development co-occurs with developmental changes in the underlying neural correlates; that is, children show compensatory activation in the lateral prefrontal cortex during inhibition (Durston et al., 2002; Luna et al., 2010) and with increasing age this activation becomes more focalized to the rIFG (Durston et al., 2002). However, much less is known about the development of intentional inhibition.

One way in which the development of intentional inhibition has been studied, is with a heart rate study using the marble paradigm (Schel et al., 2013). Three age-groups (8–10, 11–12, and 18–26 year olds) performed the marble task, while their heart rate was measured continuously. As with the analysis of heart rate responses in adults, the following conditions were dissociated: actions on the externally driven green action trials, omissions on the externally driven green action trials, decision to act on the intentional white trials, and decisions to inhibit on the intentional white trials. The results showed that 8–10 year-old and 11–12 year-old children did not differ in intentional inhibition decisions from adults; all participants decided to inhibit on approximately 50% of the trials (see Fig. 2B). All age groups showed anticipatory heart rate deceleration for all conditions. Also, all age groups showed continued heart rate deceleration in both the intentional action and the intentional inhibition conditions (see Fig. 2C). Thus, in this study we have shown that 8–10 year-old children are already able to intentionally inhibit response to a similar extent as adults. Also, heart rate was most sensitive to intentional inhibition across age groups. For all age groups, a pronounced heart rate deceleration during intentional inhibition was found, indicative of involvement of a supervisory attentional system (Schel et al., 2013).

The marble paradigm has also been applied in a cross-sectional developmental fMRI study to examine the development
of the neural bases underlying intentional inhibition (Schel, Ridderinkhof, & Crone, 2014). In this study two age-groups (10–12 and 18–26) performed the marble task while fMRI data were acquired. The results of this study showed a replication of the early development of intentional inhibition, by showing that both children and adults decided to inhibit on approximately 50% of the trials. However, although performance was similar, the underlying neural mechanisms were different in children (Schel, Ridderinkhof et al., 2014). That is, compared to adults, children showed increased activation during intentional inhibition relative to intentional action in rIFG and right putamen, key regions of the fronto-basal ganglia network for inhibition (Aron & Poldrack, 2006; Ridderinkhof et al., 2011). However, no developmental differences in dFMC activation during intentional inhibition were observed (Schel, Ridderinkhof et al., 2014).

Thus, in contrast to stimulus-driven inhibition, intentional inhibition as measured with the marble paradigm appears to have a relatively early developmental trajectory (Schel, Ridderinkhof et al., 2014; Schel et al., 2013). This idea was reinforced by the absence of covert heart rate differences in response to intentional inhibition demands. However, the underlying neural correlates differed between children and adults (Schel, Ridderinkhof et al., 2014), yet, these differences emerged in the brain network which is typically associated with externally guided inhibition, not in the dFMC. Thus, it remains a question for future research whether intentional action control is a process which develops before externally guided action control.

An additional question, which was previously addressed in a behavioral study, was whether intentional inhibition was influenced by motivational or affective context. In daily life, we often experience strong motivations for action and inhibition, and inhibition rarely happens in an affectively neutral context. A previous study showed that stimulus-driven inhibition appears to be influenced by affective context (Tottenham, Hare, & Casey, 2011). In this study, participants were instructed to respond to face stimuli expressing a certain emotion and inhibit responding to faces expressing a different emotion. Four different emotional expressions were included, three negative emotions (fear, anger and sadness), and one positive emotion (happiness), and in each block a different emotional face was coupled with neutral faces, to examine whether response inhibition was differently influenced by neutral versus emotional faces. In a developmental sample (5–28 year olds) it was found that response inhibition performance was most negatively influenced by emotions for which emotion recognition was worst, namely for anger and sadness (Tottenham et al., 2011). Also, irrelevant emotional background stimuli appeared to influence response inhibition performance (Cohen-Gilbert & Thomas, 2013; Krypotos, Jahfari, van Ast, Kindt, & Forstmann, 2011; Verbruggen & De Houver, 2007). Importantly, these effects appear to be dependent on arousal, such that highly arousing pictures have a stronger influence on response inhibition (Verbruggen & De Houver, 2007). Also, it was found that this influence of irrelevant emotional stimuli on response inhibition was larger for individuals who showed more heart rate variability (a proxy of emotion regulation) (Krypotos et al., 2011). These findings made us hypothesize that possibly also intentional inhibition would be affected by motivational context and possibly more so in children and adolescents than in adults.

In order to examine whether intentional inhibition was influenced by affective context, Schel and Crone (2013) performed an intentional inhibition experiment in which colors were the relevant dimension (i.e. the colors indicated whether participants had to act, inhibit, or choose between acting and inhibiting) and emotion was an irrelevant dimension. In this study it was found that across development, irrelevant emotions had no influence on intentional inhibition decisions (Schel & Crone, 2013). However, it remains an important question for future research whether the same is true when emotion is relevant for the task at hand. For example, one study found that emotional faces in a go/no go task were associated with more activation in ventral striatum (a region important for reward processing) in adolescents compared to children and adults when this cue was relevant to the task (Somerville, Hare, & Casey, 2011).

These differences when emotional stimuli are behaviorally relevant or incidental may also be important when studying the neural correlates of intentional inhibition. Kühn and colleagues used this approach in an fMRI study comparing the intentional and stimulus-driven inhibition of experiencing emotion (Kühn, Haggard, & Brass, 2013). In this study they showed that intentional and stimulus-driven inhibition of experiencing emotions could be dissociated on the basis of underlying neural mechanisms. Intentional inhibition of experiencing emotions was associated with activation of the dFMC, the same brain region implicated in intentional inhibition of action (Brass & Haggard, 2007; Kühn et al., 2009; Schel et al., 2014), whereas stimulus-driven inhibition of experiencing emotions was associated with activation in the dorsolateral prefrontal cortex (Kühn et al., 2013). Thus, there is a promising potential of studying the development of intentional inhibition using affective stimuli as the focus of action or inhibition.

4. The development of self-control: inhibition in order to maximize future rewards

As outlined above, exerting self-control, and especially intentional inhibition, rarely happens in affectively neutral contexts in daily life. It has been shown that both relevant and irrelevant affective contexts influence stimulus-driven inhibition (Cohen-Gilbert & Thomas, 2013; Somerville et al., 2011; Tottenham et al., 2011), but an irrelevant affective context does not appear to influence intentional inhibition decisions (Schel & Crone, 2013). However, the mere presence of an affective context does not necessarily impose motivational forces, which can influence intentional decisions; therefore looking at the influence of rewards might be a fruitful research direction.

An important motivator for self-control concerns determining the balance between preferring small immediate rewards over larger delayed rewards, a process also referred to as delay of gratification (Mischel, Shoda, & Rodriguez, 1989), or delay discounting (Ainslie, 2005; Green, Fry, & Myerson, 1994). Paradigms tapping into these processes are highly applicable to understanding intentional components of self-control, because in such paradigms, participants have control over whether to act and receive the immediate reward, or to control the tendency to act by inhibiting and waiting for the delayed reward. A classic developmental paradigm in which these motivational forces are clearly present is the delay of gratification paradigm, also referred to as the marshmallow test. This delay of gratification paradigm for preschoolers presents children with one pair of two options: one marshmallow now, or two marshmallows after an unspecified delay (later, when the experimenter returns (Mischel et al., 1989)). Studies using this paradigm have shown that there are individual differences in the ability to inhibit the impulse to choose the immediately gratifying option of one marshmallow during the preschool ages (Mischel et al., 1989), which appear to be predictive for self-control abilities later in life (Casey et al., 2011; Esgit et al., 2006). In addition, Casey and colleagues found that individuals who were less able to delay gratification when they were preschoolers, showed poorer self-control and differential recruitment of the fronto-basal ganglia network during an emotional go/no go paradigm 40 years later (Casey et al., 2011), suggesting that these early individual differences reflect temperament characteristics with long term effects.
In addition to these individual differences, several studies have reported that preferences for small immediate rewards tend to decrease as a function of age, suggesting that self-control increases with age (Christakou, Brammer, & Rubia, 2011; de Water, Cillesen, & Scheres, 2014; Lee et al., 2013; Olson, Hooper, Collins, & Luciana, 2007; Prencipe et al., 2011; Scheres et al., 2006; Steinberg et al., 2009). Unlike individual differences during the preschool years, these age effects have been examined with delay discounting (DD) tasks, consisting of a series of, often hypothetical, choice pairs (rather than only one in the marshmallow test) between monetary rewards (rather than marshmallows). A further distinction between the tasks is that the constant temptation to take the immediate reward (1 marshmallow in front of the child) in the delay of gratification paradigm while the child is waiting for the experimenter, is not present in delay discounting tasks. The delay is not experienced, and in real DD tasks, participants cannot change their mind once they have decided to choose the large delayed reward. Therefore, it is likely that self-control, while also the experimenter, is not present in delay discounting tasks. Note, however, that the only longitudinal study on delay discounting paradigms. Keeping this in mind, we will briefly summarize the age effects on self-control as measured with DD tasks. The task that is most comparable to the marshmallow task is the airplane task, developed by Scheres et al. (2006). In this task, participants choose between a variable small reward that would be immediately delivered and a large constant reward that would be delivered after a variable delay. Importantly, participants really had to wait during the delay period, when choosing for the delayed reward (see Fig. 3A), and money was actually paid to participants. Age comparisons between children aged 6–11 and adolescents aged 12–17 showed that adolescents were more likely to prefer the delayed reward compared to children (see Fig. 3B). These findings fit well with theoretical delay tasks, in which there were only hypothetical delay periods and monetary rewards, but in which participants could choose between a small immediate and a larger delayed reward (Christakou et al., 2011; de Water et al., 2014; Lee et al., 2013; Steinberg et al., 2009), and with potentially real tasks, in which participants are informed that one choice will be randomly selected and paid to them (Olson et al., 2007; Prencipe et al., 2011). These studies also reported an increasing preference for delayed rewards during adolescence. Note, however, that the only longitudinal study on delay discounting reported preferences in a potentially real task to be stable during adolescence (Audrain-McGovern et al., 2009). Similarly, Lamm, Zelazo, and Lewis (2006) reported no significant changes in potentially real delay discounting from 9 to 17 years of age. In addition, two studies, one with a hypothetical task and one with a real task (the airplane game) reported non-linear effects of age: 11–13 year olds showed maximal ability to wait relative to 8–10 and 14–16 year olds in a hypothetical tasks (Demurie, Roeyers, Baeyens, & Sonuga-Barke, 2012a), while in the airplane game, adolescents showed maximal ability to wait (peaking at age 14) as compared to children and emerging adults (Scheres, Tontsch, Thoeny, & Sumiya, 2014).

In adults a network of brain regions, including medial prefrontal cortex (mPFC), ventral striatum, and posterior cingulate cortex (PCC) regions involved in the valuation of immediate rewards, and posterior parietal cortex (PPC), dorsolateral prefrontal cortex (dPFC), and ventrolateral prefrontal cortex (vPFC) regions involved in the valuation of immediate and delayed rewards, is associated with hypothetical delay discounting (for a review, see Scheres, De Water, and Mies (2013)). In a study comparing adolescents and adults it was found that adults made more consistent decisions. Compared to adolescents, adults showed more parietal cortex activation during decision making on a hypothetical delay discounting task, which was associated with more consistent decision making (Ripke et al., 2012). Another developmental study showed that older participants showed stronger functional connectivity between ventromedial prefrontal cortex (vmPFC) and striatal areas during selection of immediate options (Christakou et al., 2011). Peper et al. (2013) also showed that in adults increased structural connectivity between frontal and striatal regions was associated with better impulse control on a temporal discounting paradigm.

To our knowledge, no study has yet examined the neural correlates of actual waiting for delayed rewards during real delay discounting tasks across development, which entails the intentional inhibition of an (tempting) action. Our prediction would be that waiting for the delayed reward will be associated with increased activity in the dFMC, a region which partly overlaps with the mPFC region associated with hypothetical discounting. Currently, only a few studies have focused on the inhibition of tempting actions and these studies were all based on adults. These studies have shown that in adults, inhibiting the temptation to continue gambling (Campbell-Meiklejohn, Woolrich, Passingham, & Rogers, 2008), and inhibiting a craving for cigarettes (Brody et al., 2007) both activate the dFMC, the same region implicated in intentional inhibition of motoric actions (Brass & Haggard, 2007; Kühn et al., 2009; Schel et al., 2014). Given that developmental differences seem present mostly when there is a strong motivation to act, an important model for future research will be to test the interplay between activity in brain regions which drive emotions and brain regions which ‘veto’ our motives to act, which will allow us to understand self-control from a broader perspective, integrating knowledge from externally-guided response control, motivation, and internal self-control.
5. Implications for developmental disorders

There are several childhood/adolescence disorders, which are associated with difficulties with self-control, such as Attention Deficit Hyperactivity Disorder (ADHD) (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), oppositional defiant disorder/conduct disorder (ODD/CD) (Nigg, 2003), and substance abuse (Wills & Stoolmiller, 2002). Traditionally, these disorders have been examined from a self-control perspective using externally driven inhibition tasks, with mixed results. For example, meta-analyses of studies using externally driven inhibition tasks have shown that there are clear inhibition problems in children and adults with ADHD (Lijffijt, Kenemans, Verbaten, & van Engeland, 2005; Oosterlaan, Logan, & Sergeant, 1998; Willcutt et al., 2005). However, effect sizes are small to moderate, and not all children with ADHD have problems with externally driven inhibition (Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005). In terms of neurobiological correlates, the results of prior studies have shown that children and adults with ADHD show decreased recruitment of the fronto-basal ganglia network (including rIFG) during externally driven response inhibition compared to healthy controls (for meta-analyses, see Cortese et al. (2012) and Hart, Radua, Nakao, Mataix-Cols, and Rubia (2013)).

One interesting direction for future research on self-control in ADHD, will be to examine the role of intentional inhibition, given that in many daily life situations, children need to control impulses such as wanting to get up of their chair and walk around in the classroom. These types of behavior, which are typical of children with ADHD or conduct disorder, often require an internal decision to inhibit, or veto, actions. The behavioral paradigms and neurobiological model proposed here provide a promising starting point for examining intentional inhibition in these disorders. Additionally, as children grow up, adults expect an increasing ability to intentionally inhibit actions. Specifically, when still in their childhood, individuals with ADHD will more often than not have adults in their proximity who serve as external drivers of self-controlled behaviors. However, as individuals with ADHD get older, the demands on internally driven inhibition will only increase. For example, in high school and beyond, it is expected that students demonstrate self-controlled behaviors with less and less assistance from others. Therefore, an intriguing hypothesis, which could be addressed in future research, is that the development of intentional inhibition may play a role in the remission versus persistence of ADHD symptoms over time.

A promising start for studying intentional inhibition in motivationally relevant contexts in individuals with ADHD has been made in research employing delay discounting tasks (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Demurie, Roeyers, Baevens, & Sonuga-Barke, 2012b; Hurt, Kepley, McCalla, & Livermore, 2011; Paloyelis, Asherson, Mehta, Faraone, & Kuntsi, 2010; Plichota et al., 2009; Scheres et al., 2006; Scheres, Tontsch, Thoeny, & Kaczkurkin, 2010; Wilson, Mitchell, Musser, Schmitt, & Nigg, 2011) or choice delay tasks (Solanto et al., 2001; Sonuga-Barke, Taylor, Semb, & Smith, 1992; for a review, see Luman, Oosterlaan, and Sergeant (2005)). These tasks are relevant here, because participants have control over whether or not to control the tendency to act by inhibiting and waiting for the delayed reward. If these tasks are viewed as measures of intentional inhibition, a preliminary conclusion would be that those with ADHD have relatively weak intentional inhibition, since the majority of studies have demonstrated that individuals with ADHD chose not to control the tendency to act and prefer the immediate reward. However, we note here that additional processes are involved in delay discounting tasks such as delay aversion, subjectively experienced difficulty waiting, and sensitivity to reward magnitude and reward immediacy (Marco et al., 2009; Scheres, Tontsch, & Thoeny, 2013; Scheres et al., 2010). Additionally, a substantial portion of these studies made use of hypothetical tasks, reducing the demand on intentional inhibition to resist a temptation. Therefore, other paradigms may be more suitable for measuring intentional inhibition in individuals with ADHD, both in cool contexts, such as the marble paradigm (Kühn et al., 2009), and in hot contexts, such as the marshmallow paradigm (Michel et al., 1989) or an emotion regulation paradigm (Kühn et al., 2013). A better understanding of the typical development of the underlying mechanisms of the ability to intentionally inhibit tempting actions will help to better understand developmental disorders of impulsivity such as ADHD. Currently, many children with ADHD receive cognitive behavioral therapy focused on the use of external reinforcers in order to stimulate positive behavior (Serrano-Troncoso, Guidi, & Alda-Diez, 2013). However, an important direction for future research will be to examine whether shifting the focus to motivations and drives from within (internal processes) may help children, adolescents, and adults with ADHD to better regulate their own behavior (see also Solanto et al. (2010)).

6. Conclusion

To conclude, intentional inhibition is an important component of self-control, which should be examined from a developmental perspective. Within a cold context, intentional inhibition appears to mature early (in childhood), even though underlying neural correlates hint towards activation differences in the inhibition network between children and adults (Schel, Riddervikhof et al., 2014; Schel et al., 2013). However, when stimuli are motivationally relevant, developmental differences become more prevalent, such as in the airplane task (Scheres et al., 2006). These newly developed paradigms provide an important starting point for examining this salient, but understudied process in child and adolescent development.

Neurobiological models suggest an important role for the medial prefrontal cortex, and especially the dPMC, in intentional inhibition in both cold and motivationally relevant contexts. Studying the neurobiological development of intentional inhibition from a motivational perspective provides a promising route for future research. fMRI studies of the development of intentionally inhibiting emotions and waiting for rewards might add to our understanding of developmental disorders such as ADHD and ODD/CD and help provide new treatments tailored to the needs of children with ADHD and ODD/CD.

References


Börger, N., & van der Meere, J. (2000). Motor control and state regulation in ADHD (Lijffijt, Kenemans, Verbaten, & van Engeland, 2005; Oosterlaan, Logan, & Sergeant, 1998; Willcutt et al., 2005). In terms of neurobiological correlates, the results of prior studies have shown that children and adults with ADHD show decreased recruitment of the fronto-basal ganglia network (including rIFG) during externally driven response inhibition compared to healthy controls (for meta-analyses, see Cortese et al. (2012) and Hart, Radua, Nakao, Mataix-Cols, and Rubia (2013)).
