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Developmental change in intentional action and inhibition: A heart rate analysis

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Abstract

The ability to inhibit is a major developmental dimension. Previous studies examined developmental change in instructed inhibition. The current study, however, focused on intentional inhibition. We examined heart rate responses to intentional action and inhibition, with a focus on developmental differences. Three age groups (8–10, 11–12, and 18–26 years) performed a child-friendly marble paradigm in which they had to choose between intentionally acting on, or inhibiting, a prepotent response. As instructed, all age groups chose to intentionally inhibit on approximately 50 percent of the intentional trials. A pronounced heart rate deceleration was observed during both intentional action and intentional inhibition, but this deceleration was most pronounced for intentional inhibition. Heart rate responses did not differentiate between age groups, suggesting that intentional action and inhibition reach mature levels early in childhood.

Descriptors: Intention, Response inhibition, Action, Heart rate, Development

The ability to control our actions is of critical importance for optimal functioning in daily life. Control over our actions can be both externally driven, such as when a traffic light turns red, and internally driven, such as when deciding not to scratch an itchy mosquito bite. Externally driven action control has been extensively studied using several different paradigms, such as stop-signal tasks (Logan & Cowan, 1984) go/no-go tasks (Casey et al., 1997), and task-switching tasks (Monsell, Sumner, & Waters, 2003). In these paradigms, a stimulus indicates whether participants should inhibit a prepared or prepotent response. Successful performance on these tasks appears to rely on a lateral prefrontal-parietal network in the brain (Aron, Robbins, & Poldrack, 2004; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002), specifically, the right inferior frontal gyrus, which seems to be prominently involved in the inhibition of motoric actions (Aron, 2011; Verbruggen & Logan, 2008).

Internally driven action control, on the other hand, has been less extensively studied, most likely because of the obvious difficulty in observing internal triggers for action. The limited number of studies in this area examined the "what" and "when" components of intentional action selection (Brass & Haggard, 2008; Haggard, 2008). Tasks examining the what component of intentional action focused on voluntary action selection (e.g., participants are instructed to voluntarily select between two response options), whereas tasks examining the when component focused on voluntary action planning (e.g., participants are instructed to decide when they want to execute an instructed response). In contrast to externally driven action control, voluntary action selection and action planning are thought to rely on a different network in the brain, specifically involving the medial frontal cortex (Lau, Rogers, Haggard, & Passingham, 2004; Lau, Rogers, & Passingham, 2006).

Recently, research into internally driven action control focused on a third component of intentional action selection, namely, the "whether" component (Brass & Haggard, 2008; Haggard, 2008). The whether component captures the process of deciding between intentionally performing or intentionally inhibiting a prepared action (Brass & Haggard, 2007, 2008; Filevich, Kühn, & Haggard, 2012). Intentional inhibition has been conceptualized as a late veto process, a final check before action execution (Brass & Haggard, 2007; Filevich et al., 2012; Kühn, Haggard, & Brass, 2009). Since there is no external stimulus and no overt behavior in intentional inhibition, the process of intentional inhibition proved to be quite difficult to investigate. Recently, however, two studies examined the neural correlates of intentional inhibition using paradigms in which participants were instructed to always prepare an action, but to choose to inhibit executing this prepared action on a number of trials. These studies indicate that intentional inhibition is supported by a specific brain area in the medial frontal cortex, which can be dissociated from the areas involved in intentional action selection

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and planning, namely, the dorsal frontomedian cortex (Brass & Haggard, 2007; Kühn et al., 2009).

In the present study, we examined intentional action and inhibition by taking advantage of phasic heart rate changes, based on prior research showing that phasic heart rate is a sensitive measure of response activation and inhibition processes (Crone, Somsen, Van Beek, & van der Molen, 2004; Crone et al., 2003; Jennings, Brock, van der Molen, & Somsen, 1992; Jennings & van der Molen, 2005; Jennings, van der Molen, Pelham, Debski, & Hoza, 1997). A score of studies showed that during the anticipation and preparation of a speeded response (e.g., a go response in a go/no-go task), heart rate decelerates (Jennings & van der Molen, 2002; Van der Veen, van der Molen, & Jennings, 2000). This anticipatory heart rate deceleration is proposed to support the central inhibition of action representations (Jennings & van der Molen, 2002, 2005). When a response is made, anticipatory heart rate deceleration is followed by an acceleratory recovery (Jennings & van der Molen, 2002; Van der Veen et al., 2000). The shift from anticipatory deceleration to acceleratory recovery is dependent on reaction time vis-à-vis the R wave of the electrocardiogram (ECG), with shifts occurring earlier when the interval between the R wave to the behavioral response is short (i.e., within 350 ms) while later shifts occur with longer R wave-to-response intervals (Jennings & Wood, 1977; Somsen, Jennings, & van der Molen, 2002). The pattern of anticipatory deceleration followed by acceleratory recovery is delayed when a response is inhibited; during response inhibition, continued heart rate deceleration is observed (Börger & van der Meere, 2000; Jennings et al., 1992; Van der Veen et al., 2000). The continued heart rate deceleration during action inhibition is interpreted to reflect midbrain inhibition of action (Jennings et al., 1992; Jennings, van der Molen, & Stenger, 2008; Van der Veen et al., 2000). Until now, the existing heart rate literature only focused on the processes of external action control and inhibition, not on the processes of intentional action and inhibition. Therefore, the present study set out to examine heart rate response patterns associated with intentional action and inhibition.

We chose to examine heart rate responses to intentional inhibition by focusing on developmental differences. It is well established that externally driven action control has a protracted developmental trajectory (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston et al., 2002). The ability to inhibit is present in early childhood (Ridderinkhof, Band, & Logan, 1999; Williams, Ponesse, Schachar, Logan, & Tannock, 1999), but this ability continues to improve through adolescence (Luna, Padmanabhan, & O'Hearn, 2010; van de Laar, van den Wildenberg, van Boxtel, & van der Molen, 2011; van den Wildenberg & van der Molen, 2004). Inhibition-related heart rate deceleration has already been observed in children aged 5 to 12 (Jennings et al., 1997; van der Molen, 2000). However, inhibition-related heart deceleration was delayed in the youngest children, suggesting that with age children become more efficient in recruiting inhibitory mechanisms (van der Molen, 2000). Currently, the development of intentional action and inhibition has not been examined, most likely because of a lack of valid child-friendly paradigms.

Here, we adopted the recently developed marble task (Kühn et al., 2009), in which participants have to decide between intentionally responding or intentionally inhibiting responding to a rolling marble, to examine the developmental pattern of intentional action and inhibition. During the task, heart rate was measured continuously so as to allow for an examination of the temporal dynamics of internal action control. We expected to observe anticipatory heart rate deceleration associated with the central inhibition of action representations (Jennings & van der Molen, 2002, 2005) during both intentional action and intentional inhibition, to allow for an intentional decision to be made. During intentional action trials, we expected to observe a shift from anticipatory deceleration towards acceleratory recovery associated with response activation and execution (Jennings & van der Molen, 2002). In contrast, during intentional inhibition trials, we expected to observe continued heart rate deceleration associated with response inhibition until task completion (Börger & van der Meere, 2000; Jennings et al., 1992, 1997; Van der Veen et al., 2000). Furthermore, with regard to the developmental pattern, we expected to observe an early development of intentional action and inhibition abilities (Ridderinkhof et al., 1999; Williams et al., 1999), but a possible delay in reaching the maximum inhibition-related heart rate deceleration in the youngest children (van der Molen, 2000).

Method

Participants

Sixty healthy participants across three age groups participated in the experiment. Three participants were excluded from the study, one because of technical difficulties, one because of misunderstanding of the experimental task, and one because of deviant heart rate responses. The final sample consisted of 24 children between 8–10 years of age (14 females, $M = 9.42$, $SD = .63$), 15 early adolescents between 11–12 years of age (6 females, $M = 12.22$, $SD = .44$), and 18 adults between 18–26 years of age (10 females, $M = 21.91$, $SD = 2.55$). A chi-square test revealed no significant differences in gender distributions between age groups ($p = .51$). Children were recruited from a primary school in the Netherlands, and informed consent was obtained from a primary caregiver. Adult participants were recruited from Leiden University and signed informed consent before participation in the experiment. All participants completed the Raven Standard Progressive Matrices (Raven SPM) to obtain an estimate of their cognitive functioning (Raven, Raven, & Court, 1998). Age groups did not differ in estimated IQ scores, $F(2,56) = 1.97$, $p = .15$, $\eta_p^2 = .07$.

Task

The marble task was adapted from Kühn et al. (2009), and optimized for heart rate recording. Each trial (see Figure 1) started with the presentation of a fixation screen (white cross against a black background) with duration jittered between 1,400 and 2,000 ms. The fixation screen was followed by a screen showing a white ramp with a white marble on top presented against a black background. After a variable duration of 1,400 to 2,000 ms, the marble started rolling down the ramp, and participants could stop the marble from crashing by pressing a button. Finally, a feedback screen, showing trial outcome, was presented for 1,000 ms. There were two task conditions: a green marble and a white marble condition.

In the green marble condition, the white marble changed to green as soon as it started rolling. The task was programmed in such a way that participants viewed 16 rapidly presented static pictures showing the marble at successive locations on the ramp, which was experienced as a rolling movement. Participants were instructed to stop the marble from crashing by pressing a response button with their right index finger. When participants were successful at stopping the marble, they were presented with a feedback screen showing the location where they had stopped the marble.

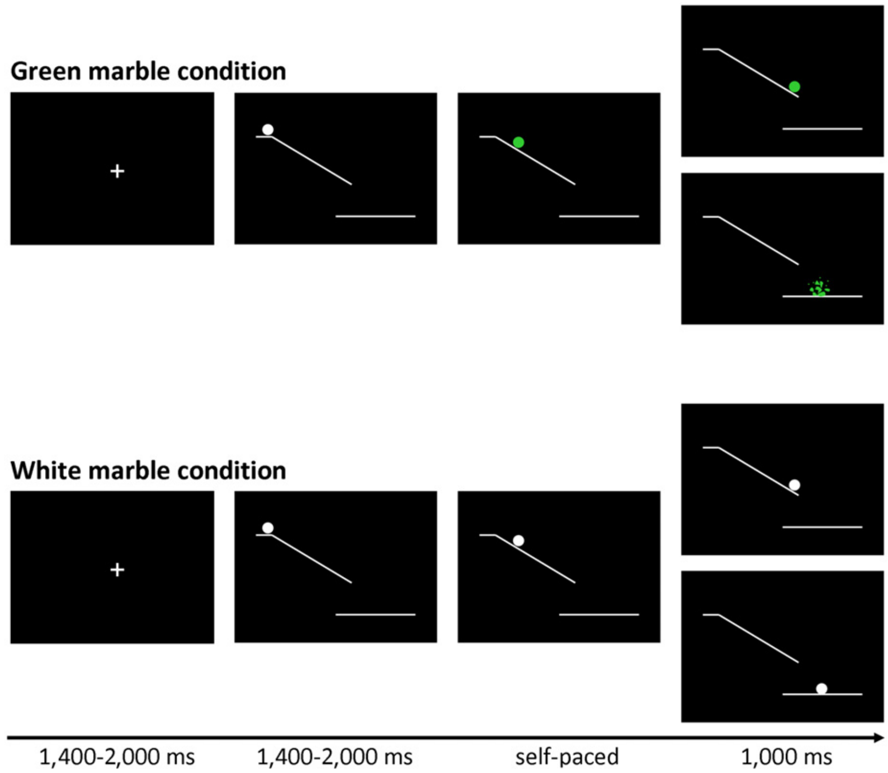

Figure 1. Trial structure. Stimuli were presented on a black background. At the beginning of each trial, a white marble on top of a ramp was presented. After a variable delay (jittered between 1,400 and 2,000 ms), the marble started to roll down the ramp, and could change color to green.

When participants were not successful at stopping the marble, they were presented with a feedback screen showing a shattered marble beneath the ramp. The speed of the marble was adjusted by a staircase procedure. At the start of the experiment, the static pictures were presented for 30 ms each. When participants were successful at stopping the marble, the duration was decreased by 10 ms, making the task more difficult. When participants were not successful at stopping the marble in time, the duration was increased by 10 ms, making the task easier. The staircase procedure was allowed to fluctuate between 20 and 80 ms, allowing a response window between 320 and 1,280 ms.

In the white marble condition, the marble did not change color, and participants were instructed to choose between responding and inhibiting. When participants responded, they were presented with a feedback screen showing the location where they had stopped the marble. When participants inhibited, they were shown a feedback screen showing the white marble at the bottom of the ramp. In order to motivate participants to balance the frequency of responding and inhibiting, they were told that the stopped and nonstopped marbles would fall in different baskets. Participants were instructed to collect an approximately equal amount of marbles in each basket, but were not allowed to count or use a sequencing strategy. At the end of each block, participants were shown how many marbles they had collected in each basket.

In order to give participants sufficient time to decide between responding and inhibiting, the speed of the white marble rolling down the ramp was set considerably slower. The speed of the sequentially presented static white marble pictures was set to the speed currently reached in the green marble condition plus 30 ms. Consequently, the duration of the sequentially presented static white marble pictures was allowed to fluctuate between 50 and 110 ms, allowing a response window between 800 and 1,760 ms.

The experiment consisted of two blocks of 80 trials (160 trials in total). Each block consisted of 48 green and 32 white marble trials. The larger proportion of green trials was included to create a prepotent action tendency, so that intentional inhibition would involve a late veto on an already prepared action. Trials were presented in a pseudorandomized order so that each white marble trial was preceded by 0, 1, 2, or 3 green marble trials. The pseudorandomized interleaving of green (instructed) and white (intentional) trials discouraged participants from strategically adopting a pattern of intentional action and inhibition, such as act-inhibit-act-inhibit, etc.

Procedure

All participants were tested individually in a laboratory or an empty classroom. Before testing, participants were instructed on the marble task. It was stressed that participants were not supposed to use a specific strategy to decide when to stop the white marble. Care was taken that all participants understood the instructions and were able to perform the task. All participants completed a practice block of 10 trials. Hereafter, participants completed the two test blocks. Including instructions, the task took approximately 20 min to complete. After completion of the task, participants were asked whether they had used a specific strategy in the task. Finally, participants completed the Raven SPM.

Data Recording and Analysis

During the task, the ECG was measured continuously using the Biopac System at a sample frequency of 400 Hz. The ECG was recorded from three Ag-Ag/Cl electrodes, attached via the modified lead-two placement (one electrode directly under the right collar bone, one electrode between the two lower left ribs, and the ground electrode directly right of the navel). Interbeat intervals (IBIs) were defined as the length between consecutive R peaks. The R peaks were detected with the program PhysioSpec (developed by Technical Support Group UvA Psychology). The recorded IBIs were screened for physiologically impossible readings and artifacts (i.e., R peaks not detected or other peaks seen as R peaks). These were corrected by adjusting specific parameters in the program that extracted the IBIs from the digitized ECGs. Five consecutive IBIs were selected around the onset of marble motion: the IBI concurrent with the onset of marble motion (IBI 0), two IBIs preceding the onset of marble motion (IBI −2 and IBI −1), and two IBIs following the onset of marble motion (IBI 1 and IBI 2). In order to obtain an index of phasic heart rate change (IBI difference), IBIs were referenced to IBI-2. Preliminary analysis of IBI-2 revealed no significant differences in IBI length between the different test conditions, confirming that there were no a priori differences between these conditions reflected in heart rate. Statistical analyses were performed using repeated measures analysis of variance (ANOVA). Huynh-Feldt corrections for violations of the assumption of sphericity were used when necessary (Jennings, 1987; Vasey & Thayer, 1987).

Results

Behavior

An age group (3) ANOVA for the number of go responses on the green trials showed that, with increasing age, participants became more successful at responding to the green marble in time, $F(2,56) = 20.02$, $p < .001$, $\eta_p^2 = .43$. Post hoc Tukey tests showed that adults were more successful at responding fast to the green marble compared to both children ($p < .001$) and early adolescents ($p < .01$) (see Figure 2). Children and early adolescents did not differ significantly in their ability to respond to the green marble in time ($p = .078$).

On average, participants decided to inhibit responding to the white marble on 43.64 percent of the trials. Age groups did not differ in this regard, $F(2,56) = .826$, $p = .44$, $\eta_p^2 = .03$ (children: $M = 42.58$, $SD = 15.99$; early adolescents: $M = 41.35$, $SD = 15.69$; adults: $M = 46.96$, $SD = 6.00$) (see Figure 2). This finding indicates that all age groups performed the intentional inhibition task as instructed.

The use of strategies was evaluated by computing the Random Number Generation 2 (RNG2) index using Towse and Neil's (1998) RgCalc program. The RNG2 index is an adaptation of the random number generation index (Evans, 1978) optimized for two-choice response sequences, which considers the randomness of the sequence (Neuringer, 1986). A mean RNG2 index of .784 ($SD = .025$) was observed. Age groups did not differ in RNG2 index, $F(2,56) = 2.55$, $p = .088$, $\eta_p^2 = .09$ (children: $M = .789$, $SD = .021$; early adolescents: $M = .790$, $SD = .038$; adults: $M = .774$, $SD = .007$). To examine the randomness, the participants' RNG2 index was compared with a RNG2 index computed over a set of randomly generated sequences of go and no-go responses. For the randomly generated set of go and no-go response sequences, a mean RNG2 index of .770 ($SD = .001$) was observed. Adults' RNG2 index did not differ from the RNG2 index for the randomly generated set of go and no-go responses ($p = .10$), indicating that their choice behavior was not guided by unwanted rules (e.g., alternating between go vs. no-go). RNG2 indexes of both children and early adolescents differed significantly from the RNG2 index for the randomly generated set of go and no-go responses (all ps $< .05$), indicating that children's and early adolescents' choice behavior deviated from pure randomness.

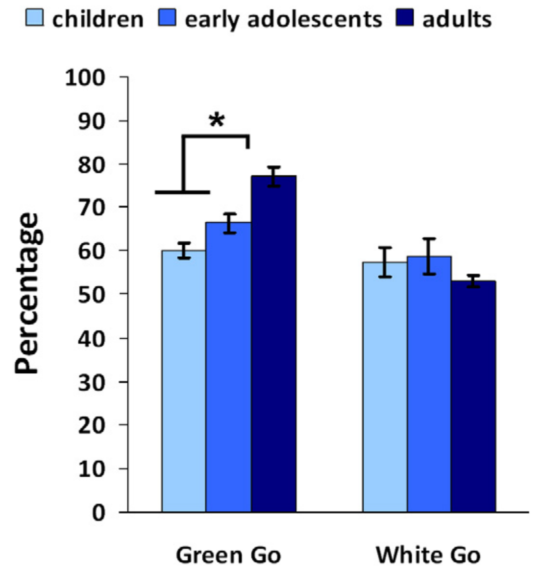

Figure 2. Percentage of go responses in the green and white marble conditions.

Reaction times were shorter for the green marble trials ($M = 283.92$, $SE = 6.85$) than for the white marble trials ($M = 358.77$, $SE = 11.78$), $F(1,54) = 97.39$, $p < .001$, $\eta_p^2 = .64$. Overall, reaction times decreased with age, $F(2,54) = 3.47$, $p < .05$, $\eta_p^2 = .11$. Post hoc Tukey tests showed that children were slower compared to adults ($p < .05$). Reaction times did not differ between children and early adolescents ($p = .41$) and between early adolescents and adults ($p = .50$). However, no interaction with condition was observed ($p = .68$). Together, these results indicate that all age groups performed the task accurately, but that adults were more efficient in doing so, as indicated by faster responses to green trials and more random choice behavior on the white trials.

Heart Rate

IBIs were computed separately for the stimulus-driven green go condition, omissions on the stimulus-driven green trials, and the intentional white go and white no-go conditions. To test for differences in heart rate responses between the stimulus-driven and intentional conditions, an Age group (3) × Condition (2: green and white) × Response (2: go and no-go) × IBI (4) repeated measures ANOVA was performed. This analysis resulted in a main effect of IBI, $F(3,162) = 58.80$, $p < .001$, $\eta_p^2 = .52$, $\varepsilon = .67$. As can be seen in Figure 3, heart rate decelerated (i.e., slowed) in anticipation of stimulus presentation, followed by an acceleratory recovery. A Condition × IBI interaction, $F(3,162) = 17.39$, $p < .001$, $\eta_p^2 = .24$, $\varepsilon = .83$, indicated that heart rate deceleration was more pronounced for the intentional compared to the stimulus-driven conditions. A Response × IBI interaction, $F(3,162) = 28.00$, $p < .001$, $\eta_p^2 = .34$, $\varepsilon = .86$, indicated that the shift from anticipatory deceleration to

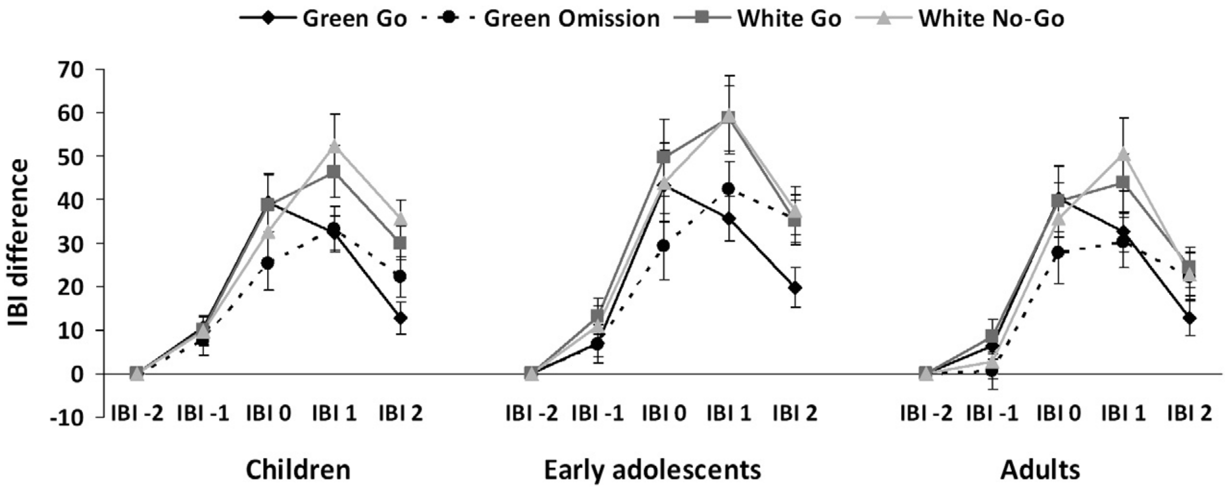

Figure 3. Stimulus-locked heart rate changes associated with stimulus-driven action, omissions on stimulus-driven action trials, intentional action, and intentional inhibition. IBI 0 refers to the IBI during which the marble started to roll down the ramp. An increase in IBI difference scores indicates heart rate deceleration, and a decrease in IBI difference scores indicates heart rate acceleration.

acceleratory recovery occurred earlier for go compared to no-go responses. Furthermore, a Condition × Response × IBI interaction, $F(3,162) = 7.10$, $p < .001$, $\eta_p^2 = .12$, $\varepsilon = .93$, was observed, indicating that heart rate patterns associated with go versus no-go responses differed depending on the condition (green/white) in which they were made. No interactions with age group were found (all 2-, 3-, and 4-way interactions, $ps > .1$), demonstrating that heart rate responses to the different conditions were similar across age groups.

Follow-up ANOVAs for the green stimulus-driven and white intentional conditions separately showed that within the stimulus-driven condition the shift from anticipatory deceleration to acceleratory recovery occurred earlier for go compared to no-go responses, $F(3,168) = 31.08$, $p < .001$, $\eta_p^2 = .36$, $\varepsilon = .88$. For no-go responses, heart rate continued to decelerate during IBI 1, indicative of a lapse of attention. In the intentional condition, heart rate deceleration was more pronounced for intentional inhibition compared to intentional action, $F(3,168) = 5.93$, $p < .002$, $\eta_p^2 = .10$, $\varepsilon = .90$. Follow-up ANOVAs for the go and no-go responses separately showed that for the no-go responses heart deceleration was more pronounced in the white intentional compared to the green stimulus-driven condition, $F(3,168) = 9.11$, $p < .001$, $\eta_p^2 = .14$, $\varepsilon = .90$. Furthermore, heart rate deceleration was also more pronounced and continued during IBI 1 for the intentional white go compared to the stimulus-driven green go responses, $F(3,168) = 21.66$, $p < .001$, $\eta_p^2 = .28$, $\varepsilon = .84$. Together, these results show that heart rate deceleration was more pronounced for the intentional conditions and that this heart rate deceleration was strongest in the intentional inhibition condition.

However, one alternative explanation for the continued heart rate deceleration in the intentional action condition is the possibility of a longer R wave-to-response interval for the white go compared to the green go condition (Jennings & Wood, 1977; Somsen et al., 2002). Since reaction times in the white go condition were slower compared to the green go condition, it might be that responses in the white go condition occurred later in the IBI, resulting in a longer R wave-to-response interval. To control for this alternative explanation, we performed a response-locked analysis (Jennings, van der Molen, Somsen, & Terezis, 1990). For this analysis, five IBIs were selected around the moment of responding, IBI −2 to IBI 2; the moment of responding occurred during IBI 0. IBIs were referenced to IBI −2 to create IBI difference scores. Preliminary analysis of raw IBI −2 values revealed no significant difference in IBI −2 length between the white go and the green go conditions, confirming that there were no a priori differences between those conditions reflected in heart rate.

To test for differences in heart rate responses between the white go and the green go conditions, an Age group (3) × Condition (2) × IBI (4) repeated measures ANOVA was performed. Importantly, this analysis showed again a more pronounced heart rate deceleration for the white go compared to the green go condition, $F(3,162) = 9.86$, $p < .001$, $\eta_p^2 = .15$, $\varepsilon = .88$ (see Figure 4), indicating that indeed heart rate deceleration is most pronounced for the intentional conditions. Again, no interaction with age group was found (3-way interaction, $p = .26$), demonstrating that this pattern was similar across age groups.

Discussion

In the present study, we examined the cardiac concomitants of intentional action and inhibition. Participants, divided in three age groups, performed a marble paradigm, in which they had to decide between intentionally inhibiting a response and intentionally responding to a rolling marble in the context of prepotent go responses, while their heart rate was measured continuously.

The behavioral results showed that all age groups followed task instructions: on average, age groups intentionally inhibited on 43.46% of the trials, which is close to criterion (50%). The observation that in our study even the 8- to 10-year-olds were able to intentionally inhibit a prepotent response concurs with previous studies showing an early development of the ability to inhibit (Ridderinkhof et al., 1999; Williams et al., 1999). Importantly, analysis of the RNG2 index (Evans, 1978; Neuringer, 1986) indicated that participants did not use a simple alternation strategy to decide whether or not to inhibit responding to the white marble. Adults' choice behavior did not differ from a randomly generated response sequence whereas the choice behavior of children and

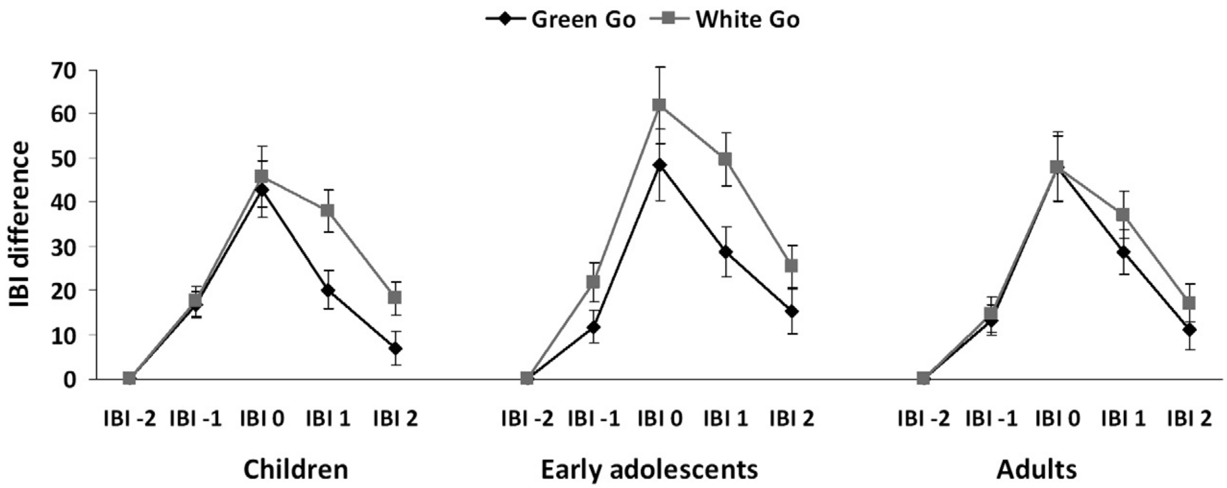

Figure 4. Response-locked heart rate changes associated with stimulus-driven action and intentional action. IBI 0 refers to the IBI during which the participant responded. An increase in IBI difference scores indicates heart rate deceleration, and a decrease in IBI difference scores indicates heart rate acceleration.

early adolescents did, which is consistent with previous research showing a protracted development of random sequence generation (Towse & Mclachlan, 1999).

Consistent with the results of Kühn and colleagues (2009), we observed longer reaction times for the intentional go responses compared to the stimulus-driven go responses, indicating that the intentional decision process takes more time. Children and early adolescents responded slower compared to adults on both the stimulus-driven and the intentional trials, indicating that children and early adolescents were less efficient in performing the go task. Even though a tracking system was used to adapt speed of responding to average reaction times on the stimulus-driven trials, children and adolescents were still less able to respond to this deadline on all trials, suggesting that there was more variability in their response times (Tamnes, Fjell, Westlye, Ostby, & Walhovd, 2012). Importantly, for the reaction times, no interaction between condition (stimulus-driven, intentional) and age group was found, indicating that intentional go responses were not disproportionally more difficult than stimulus-driven go responses for children and early adolescents compared to adults.

The observed pattern of anticipatory heart rate deceleration and acceleratory recovery in our task is consistent with the standard pattern found in the stimulus-driven action control literature (Jennings et al., 1992; Jennings & van der Molen, 2002, 2005; van Boxtel, van der Molen, Jennings, & Brunia, 2001; Van der Veen et al., 2000). In addition, during intentional inhibition a pronounced continued heart rate deceleration was observed. This is in line with previous heart rate studies focusing on stimulus-driven inhibition (van Boxtel et al., 2001; Van der Veen et al., 2000), in which also heart rate deceleration following action inhibition was observed. Interestingly, we also observed a continued heart rate deceleration during intentional action, although less pronounced as for intentional inhibition, suggesting that heart rate is also sensitive to volitional decisions. The observed heart rate deceleration during intentional action remained significant when a response-locked analysis was performed to control for possible differences in R wave-to-response intervals between the stimulus-driven and the intentional conditions.

The findings suggest that heart rate deceleration in the context of the current intentional action and inhibition paradigm is an index of a supervisory attention system for the central regulation of voluntary behavior (Jennings & van der Molen, 2002; Norman & Shallice, 1986). The observation of heart rate deceleration in the context of intentional action is consistent with earlier results showing heart rate deceleration when delaying action (Jennings, van der Molen, & Debski, 2003). In the intentional action condition, participants are also delaying their action until they have made a final decision whether or not to act. The same is true for the intentional inhibition condition; in this case, participants are also delaying their action until they have made a final decision whether or not to act, but here the final decision is an inhibition instead of an overt action.

We did not observe developmental differences in intentional action and inhibition, indicating that the mechanics for intentional action and inhibition are already in place in middle childhood. Notably, the pattern of heart rate responses suggested that there were also no developmental differences across the age groups examined in the efficiency of recruiting the inhibitory mechanism. One possible explanation for this observation could be the mediating role of internal motivation. When one intentionally decides to inhibit, internal motivation to inhibit will be higher compared to when an external stimulus signals that one has to inhibit. Previous research has shown that motivation indeed plays an important role in inhibition (Groom et al., 2010; Leotti & Wager, 2010; Sinopoli, Schachar, & Dennis, 2011). For example, inhibitory performance improves when monetary incentives are used (Leotti & Wager, 2010; Sinopoli et al., 2011). Motivation also has a positive effect on electrophysiological markers of response inhibition (Groom et al., 2010). This finding is consistent with our observation that children and early adolescents showed adult-like heart rate response patterns for the internally motivated intentional conditions.

One limitation to the present study is the relatively restricted age range. Future studies should include younger age groups for a full assessment of developmental change in intentional inhibition. Most likely, this will require some further adaptations of the marble task, making it even more child-friendly than the current version.

Taken together, the present study was the first to examine heart rate responses to intentional action and inhibition. Both intentional action and intentional inhibition resulted in heart rate deceleration, although the deceleration was larger for intentional inhibition than for intentional action. Thus, both volitional processes and inhibition may drive heart rate deceleration. This extends the existing heart rate literature by showing that not only externally driven effortful processing, but also internally driven volitional processing affects heart rate responses. The finding that heart rate responses to intentional action and inhibition are in place in middle childhood may indicate that internally driven choices may form a basic part of the supervisory attention system, which comes online early in development.

References

Aron, A. R. (2011). From reactive to proactive and selective control: Developing a richer model for stopping inappropriate responses. *Biological Psychiatry*, *69*, E55–E68. doi: 10.1016/j.biopsych.2010.07.024

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8*, 170–177. doi: 10.1016/j.tics.2004.02.010

Börger, N., & van der Meere, J. (2000). Motor control and state regulation in children with ADHD: A cardiac response study. *Biological Psychology*, *51*, 247–267. doi: 10.1016/s0301-0511(99)00040-x

Brass, M., & Haggard, P. (2007). To do or not to do: The neural signature of self-control. *Journal of Neuroscience*, *27*, 9141–9145. doi: 10.1523/jneurosci.0924-07.2007

Brass, M., & Haggard, P. (2008). The what, when, whether model of intentional action. *Neuroscientist*, *14*, 319–325. doi: 10.1177/1073858408317417

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*, 301–311. doi: 10.1016/s0896-6273(01)00583-9

Bunge, S. A., Hazeltine, E., Scanlon, M. D., Rosen, A. C., & Gabrieli, J. D. E. (2002). Dissociable contributions of prefrontal and parietal cortices to response selection. *Neuroimage*, *17*, 1562–1571. doi: 10.1006/nimg.2002.1252

Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., . . . Rapoport, J. L. (1997). A developmental functional MRI study of prefrontal activation during performance of a Go-No-Go task. *Journal of Cognitive Neuroscience*, *9*, 835–847. doi: 10.1162/jocn.1997.9.6.835

Crone, E. A., Somsen, R. J. M., Van Beek, B., & van der Molen, M. W. (2004). Heart rate and skin conductance analysis of antecendents and consequences of decision making. *Psychophysiology*, *41*, 531–540. doi: 10.1111/j.1469-8986.2004.00197.x

Crone, E. A., van der Veen, F. M., van der Molen, M. W., Somsen, R. J. M., van Beek, B., & Jennings, J. R. (2003). Cardiac concomitants of feedback processing. *Biological Psychology*, *64*, 143–156. doi: 10.1016/s0301-0511(03)00106-6

Durston, S., Thomas, K. M., Yang, Y. H., Ulug, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, *5*, F9–F16. doi: 10.1111/1467-7687.00235

Evans, F. J. (1978). Monitoring attention deployment by random number generation—Index to measure subjective randomness. *Bulletin of the Psychonomic Society*, *12*, 35–38.

Filevich, E., Kühn, S., & Haggard, P. (2012). Intentional inhibition in human action: The power of 'no.' *Neuroscience and Biobehavioral Reviews*, *36*, 1107–1118. doi: 10.1016/j.neubiorev.2012.01.006

Groom, M. J., Scerif, G., Liddle, P. F., Batty, M. J., Liddle, E. B., Roberts, K. L., . . . Hollis, C. (2010). Effects of motivation and medication on electrophysiological markers of response inhibition in children with attention-deficit/hyperactivity disorder. *Biological Psychiatry*, *67*, 624–631. doi: 10.1016/j.biopsych.2009.09.029

Haggard, P. (2008). Human volition: Towards a neuroscience of will. *Nature Reviews Neuroscience*, *9*, 934–946. doi: 10.1038/nrn2497

Jennings, J. R. (1987). Editorial policy on analyses of variance with repeated measures. *Psychophysiology*, *24*, 474–475. doi: 10.1111/j.1469-8986.1987.tb00320.x

Jennings, J. R., Brock, K., van der Molen, M. W., & Somsen, R. J. M. (1992). On the synchrony of stopping motor-responses and delaying heartbeats. *Journal of Experimental Psychology—Human Perception and Performance*, *18*, 422–436. doi: 10.1037/0096-1523.18.2.422

Jennings, J. R., & van der Molen, M. W. (2002). Cardiac timing and the central regulation of action. *Psychological Research—Psychologische Forschung*, *66*, 337–349. doi: 10.1007/s00426-002-0106-5

Jennings, J. R., & van der Molen, M. W. (2005). Preparation for speeded action as a psychophysiological concept. *Psychological Bulletin*, *131*, 434–459. doi: 10.1037/0033-2909.131.3.434

Jennings, J. R., van der Molen, M. W., & Debski, K. (2003). Mental rotation delays the heart beat: Probing the central processing bottleneck. *Psychophysiology*, *40*, 666–674. doi: 10.1111/1469-8986.00068

Jennings, J. R., van der Molen, M. W., Pelham, W., Debski, K. B., & Hoza, B. (1997). Inhibition in boys with attention deficit hyperactivity disorder as indexed by heart rate change. *Developmental Psychology*, *33*, 308–318. doi: 10.1037/0012-1649.33.2.308

Jennings, J. R., van der Molen, M. W., Somsen, R. J., & Terezis, C. (1990). On the shift from anticipatory heart rate deceleration to acceleratory recovery: Revisiting the role of response factors. *Psychophysiology*, *27*, 385–395. doi: 10.1111/j.1469-8986.1990.tb02332.x

Jennings, J. R., van der Molen, M. W., & Stenger, V. A. (2008). Preparation for speeded action activates cortical motor and autonomic response selection areas. *Psychophysiology*, *45*, S98–S99.

Jennings, J. R., & Wood, C. C. (1977). Cardiac cycle time effects on performance, phasic cardiac responses, and their intercorrelation in choice reaction-time. *Psychophysiology*, *14*, 297–307. doi: 10.1111/j.1469-8986.1977.tb01179.x

Kühn, S., Haggard, P., & Brass, M. (2009). Intentional inhibition: How the "veto-area" exerts control. *Human Brain Mapping*, *30*, 2834–2843. doi: 10.1002/hbm.20711

Lau, H. C., Rogers, R. D., Haggard, P., & Passingham, R. E. (2004). Attention to intention. *Science*, *303*, 1208–1210. doi: 10.1126/science.1090973

Lau, H. C., Rogers, R. D., & Passingham, R. E. (2006). Dissociating response selection and conflict in the medial frontal surface. *Neuroimage*, *29*, 446–451. doi: 10.1016/j.neuroimage.2005.07.050

Leotti, L. A., & Wager, T. D. (2010). Motivational influences on response inhibition measures. *Journal of Experimental Psychology—Human Perception and Performance*, *36*, 430–447. doi: 10.1037/a0016802

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action—A theory of an act of control. *Psychological Review*, *91*, 295–327. doi: 10.1037/0033-295x.91.3.295

Luna, B., Padmanabhan, A., & O'Hearn, K. (2010). What has fMRI told us about the development of cognitive control through adolescence? *Brain and Cognition*, *72*, 101–113. doi: 10.1016/j.bandc.2009.08.005

Monsell, S., Sumner, P., & Waters, H. (2003). Task-set reconfiguration with predictable and unpredictable task switches. *Memory & Cognition*, *31*, 327–342. doi: 10.3758/bf03194391

Neuringer, A. (1986). Can people behave "randomly"?—The role of feedback. *Journal of Experimental Psychology—General*, *115*, 62–75. doi: 10.1037/0096-3445.115.1.62

Norman, D. A., & Shallice, T. (1986). Attention to action. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation* (pp. 1–18). New York, NY: Plenum Press.

Raven, J., Raven, J. C., & Court, J. H. (1998). *Manual for Raven's progressive matrices and vocabulary scales. Section 1: General overview*. San Antonio, TX: Harcourt Assessment.

Ridderinkhof, K. R., Band, G. P. H., & Logan, G. D. (1999). A study of adaptive behavior: Effects of age and irrelevant information on the ability to inhibit one's actions. *Acta Psychologica*, *101*, 315–337.

Sinopoli, K. J., Schachar, R., & Dennis, M. (2011). Reward improves cancellation and restraint inhibition across childhood and adolescence. *Developmental Psychology*, *47*, 1479–1489. doi: 10.1037/a0024440

Somsen, R., Jennings, J. R., & van der Molen, M. (2002). Human vagal heart rate responses in warned reaction time tasks: A cross-validation with simulated vagus-sino-atrial node interactions. [Supplement]. *Journal of Electrocardiology*, *35*, 231–237. doi: 10.1054/jelc.2002.37190

Tamnes, C. K., Fjell, A. M., Westlye, L. T., Ostby, Y., & Walhovd, K. B. (2012). Becoming consistent: Developmental reductions in intraindividual variability in reaction time are related to white matter integrity. *Journal of Neuroscience*, *32*, 972–982. doi: 10.1523/Jneurosci.4779-11.2012

Towse, J. N., & Mclachlan, A. (1999). An exploration of random generation among children. *British Journal of Developmental Psychology*, *17*, 363–380. doi: 10.1348/026151099165348

Towse, J. N., & Neil, D. (1998). Analyzing human random generation behavior: A review of methods used and a computer program for describing performance. *Behavior Research Methods Instruments & Computers*, *30*, 583–591. doi: 10.3758/bf03209475

van Boxtel, G. J. M., van der Molen, M. W., Jennings, J. R., & Brunia, C. H. M. (2001). A psychophysiological analysis of inhibitory motor control in the stop-signal paradigm. *Biological Psychology*, *58*, 229–262. doi: 10.1016/s0301-0511(01)00117-x

van de Laar, M. C., van den Wildenberg, W. P., van Boxtel, G. J., & van der Molen, M. W. (2011). Lifespan changes in global and selective stopping and performance adjustments. *Frontiers in Psychology*, *2*, 357. doi: 10.3389/fpsyg.2011.00357

van den Wildenberg, W. P., & van der Molen, M. W. (2004). Developmental trends in simple and selective inhibition of compatible and incompatible responses. *Journal of Experimental Child Psychology*, *87*, 201–220. doi: 10.1016/j.jecp.2003.11.003

van der Molen, M. W. (2000). Developmental changes in inhibitory processing: Evidence from psychophysiological measures. *Biological Psychology*, *54*, 207–239. doi: 10.1016/S0301-0511(00)00057-0

Van der Veen, F. M., van der Molen, M. W., & Jennings, J. R. (2000). Selective inhibition is indexed by heart rate slowing. *Psychophysiology*, *37*, 607–613. doi: 10.1017/s0048577200982301

Vasey, M. W., & Thayer, J. F. (1987). The continuing problem of false positives in repeated measures ANOVA in psychophysiology—A multivariate solution. *Psychophysiology*, *24*, 479–486. doi: 10.1111/j.1469-8986.1987.tb00324.x

Verbruggen, F., & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Sciences*, *12*, 418–424. doi: 10.1016/j.tics.2008.07.005

Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology*, *35*, 205–213. doi: 10.1037//0012-1649.35.1.205

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