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Executive Functions and Their Differential Contribution to Sustained Attention in 5- to 8-Year-Old Children

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Abstract

Everyday routine in general and school settings in particular make high demands on children's abilities to sustain their focus of attention over longer time periods. School tasks thus require the child to accomplish the task on an appropriate level of performance while maintaining the focus of attention even under repetitious or distracting conditions. However, sustained attention (SA) may be a more heterogeneous construct than commonly assumed as it requires the individual not only to sustain attentional capacities but also to store and maintain the task rule (working memory), to inhibit inappropriate responses (inhibition), and to switch according to requirements (switching). It might thus involve processes counted among executive functions (EF). In the present study, performance in EF tasks (covering the core components inhibition, switching, and working memory) and in a SA task was assessed in 118 children, aged between 5;0 and 8;11 years. Similar age-dependent performance trajectories were found in EF components and SA, indicating ongoing performance improvements between 5 until at least 8 years of age in SA and in EF. Interrelations between single EF components and SA showed to be small to moderate. Finally, different patterns of SA performance predictions were found in age-homogeneous subgroups with inhibition being crucial for SA performance in the youngest and switching in the oldest age group. Taken as a whole, even though similarities in assumed developmental trajectories and substantial interrelations point to common underlying processes in EF and SA, age-dependent patterns of explained variance indicate clear discriminability.

Keywords: executive functions, children, inhibition, working memory, switching, sustained attention

1. Introduction

The successful execution of school tasks requires the child to maintain the focus of attention over a longer period of time, even in case of repetitions or absent immediate rewards. What is usually referred to as sustained attention (SA) comprises a variety of additional cognitive capacities along with pure attentional abilities. In order to maintain the focus of attention, the student is required to keep in mind the teacher's instructions while, at the same time, distractions such as disturbances by classmates or the glimpse of the first snow outside of the window have to be ignored. Abilities as shown here are frequently classified as components of executive functions (EF). The present study evaluates age-related changes both in the core components of EF and in the attentional component of SA. Moreover, it aims at exploring shared processes between SA and EF. Additionally, age-dependent patterns of unique and shared contributions of single EF components accounting for individual differences in SA performance were evaluated.

1.1 Executive Functions

EF are defined as a composition of multiple higher-order cognitive skills, involving the superordinate orchestration of cognitive processes by allowing target-oriented control of behavior and emotions (Anderson, 2008; Zelazo & Carlson, 2012; Zelazo, Carlson, & Kesek, 2008). Factorial structure has been evaluated with results in adults suggesting a three-factorial structure with the dissociable yet interrelated core components *Switching, Inhibition,* and *Working Memory* (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Switching describes the ability to respond to changes in the environment by flexibly adapting to the according current demands (Cragg & Nation, 2009). Inhibition denotes processes which are involved in the suppression of processing irrelevant yet dominant or prepotent stimuli or responses (Nigg, 2000). Working memory is defined as the ability to store and mentally manipulate memory contents (Davidson, Amso, Anderson, & Diamond, 2006).

In younger children, empirical evidence for the internal structure of EF is less clear with some research groups proposing only two EF factors, namely switching and working memory (Huizinga, Dolan, & van der Molen, 2006). However, other results indicate essentially the same three distinguishable factors in children as in adults, but possibly closer interrelations among these factors (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Rose, Feldman, & Jankowski, 2011).

1.2 Attention

Attention is frequently subdivided in several distinctive attentional components with the nature of these components still being debated (Steele, Karmiloff-Smith, Cornish, & Scerif, 2012). In adults as well as in 1st and 2nd grade children, Mirsky, Anthony, Duncan, Ahearn, and Kellam (1991) identified four distinctive attentional components as part of their multicomponent model of attention. According to this model, the *focus* component refers to the ability to select target information while inhibiting the processing of irrelevant elements. The ability to maintain focus and alertness over time is defined by the *sustain* component (equivalent to SA). *Shift* is defined as the capacity to change the focus of attention flexibly. As a last attentional component, Mirsky and colleagues suggested *encoding* which comprises the mnemonic aspect of attention including the ability to process information sequentially. Because of its relevance in everyday life, research efforts have frequently been directed towards the component of SA as it is regarded to represent a crucial ability both in normative (Riccio, Reynolds, Lowe, & Moore, 2002) and in clinical populations (Douglas, 1972) and thus suggests to be a highly ecologically valid construct.

Another theoretical position is taken up by Posner and Fan (2008) proposing the domain of attention consisting of attentional networks which contain differential aspects of voluntary control. The authors thus propose one attentional network being involved in orienting processes while another attentional network is assumed to focus on executive control. Steele, Karmiloff-Smith, Cornish, and Scerif (2012) adapted this theoretical model for young children and suggest attentional components being empirically differentiable, yet interrelated more closely than in adults. Based on a factor-analytical approach, the authors assume attention in early childhood (3 to 6 years of age) being classified into two attention factors; one encompassing both sustained and focused attention (consisting of SA and visual search variables), the other factor consisting of executive processes (consisting of SA commission errors and spatial conflict variables).

1.3 The Relation between EF and Attention

Considering the definitions of the components of attention, the theoretical overlap with the construct of EF becomes evident (Klenberg, Korkman, & Lahti-Nuuttila, 2001; Posner & Rothbart, 1998). Despite commonalities between the construct of attention and EF on a content level, however, the empirical relation of these two concepts is yet unclear with substantial variations among different authors, terminologies, and research traditions (Henry, 2012; Klenberg et al., 2001).

1.3.1 Commonalities between EF and Attention on the Level of Involved Processes

Integrating the above-described definitions of attention and EF, the overlap and possible congruency among both constructs becomes most evident in the component of attentional shifting – sometimes even referred to as executive attention (e.g., Posner & Rothbart, 1998) – and the EF component of switching. While attentional shifting is described as the ability to change the focus of attention flexibly and adaptively (Mirsky et al., 1991), the EF component of switching is defined as the ability to switch flexibly between tasks, operations, or mental sets (Miyake & Friedman, 2012; Miyake et al., 2000). Both the attentional and the EF component of shifting/switching describe the same cognitive ability of a disengagement of previously relevant mental sets in order to adapt to the current environmental demands. Similarity rather than overlap can be found among the attentional component of focusing and the EF component of inhibition. While attentional focusing is defined as the ability to select relevant stimuli in order to execute task demands (Mirsky et al., 1991), the EF component of inhibition denotes the somehow broader concept of deliberate inhibition of dominant, automatic, or prepotent responses or task-irrelevant stimuli (Miyake et al., 2000). The similarity becomes evident as the process of selecting relevant stimuli presupposes the prior inhibition of irrelevant but possibly prepotent responses. The aspect of the maintenance and manipulation of newly acquired memory contents refers to the attentional component of encoding and the EF component of working memory. While the component of encoding emphasizes the sequential registration and recall (Mirsky et al., 1991), the active maintenance of memory contents is focused explicitly in the EF component of working memory.

Regarding the fourth component of the multi-component model of Mirsky and colleagues (1991), SA, a similarity to the construct of EF is less evident at first sight. However, a different picture emerges if considering the level of underlying processes. SA is defined as the ability to maintain the focus continuously on specific stimuli (Reck & Hund, 2011), implying that task demands have to be remembered in the course of task execution (Betts, Mckay, Maruff, & Anderson, 2006; Caggiano & Parasuraman, 2004). Moreover, the focus of attention has to be sustained even under distracting conditions. Therefore, successful maintenance of the attentional focus necessitates the ability to inhibit the processing of potentially distracting stimuli (Davidson et al., 2006).

Despite obvious parallels between EF and SA on a theoretical level of involved processes, there is, to the best of our knowledge, no previous study exploring the relation between both constructs empirically in children. In adults, the relation between SA and working memory has been investigated by Baddeley, Cocchini, Della Sala, Logie, & Spinnler (1999). The authors suggest that, if SA tasks require controlled processes (such as the successive discrimination), then memory capacities are involved in the measured performance, leading to a decrement in SA performance. The results confirm their hypothesis of a decrease in SA performance when memory maintenance was required, thus indicating that working memory may play an important role in SA performance (Baddeley et al., 1999).

1.3.2 Developmental Trajectories as an Indicator of Similarity between EF and Attention

Comparing the developmental trajectories of EF and attention is another opportunity of discussing potential similarities in the case of resembling curves or diverging underlying processes (if the course of development differs among both constructs). This approach was pursued by Klenberg, Korkman and Lahti-Nuutila (2001) who delineated differences in developmental progression between EF and attention, indicating a discriminability of these two concepts. The authors applied different tests of attention (auditory attention, auditory response set, visual search, and visual attention), inhibition (inhibition of impulses and motor control), and complex EF (planning, problem solving, verbal fluency, design fluency) in 3- to 12-year-old children and subsequently evaluated developmental trajectories of these cognitive functions. Results revealed different age ranges of especially marked development among inhibition, attention, and complex EF with inhibition reaching ceiling at age 6. Developmental progression in attention continued until about 10 years of age with complex EF progressing until 11 years of age, suggesting attention and EF being distinct.

With regard to the attentional component of SA, substantial improvements were found in young children (3- to 6-year-olds: Steele et al., 2012), but were also shown to continue until at least 8-9 years of age with only minor further improvement thereafter (Betts et al., 2006). Rebok and colleagues (1997) found indications of ongoing development of SA until 13 years of age, as illustrated by a reduction in reaction time (RT) across age groups in a visual continuous performance task (CPT). Developmental changes in EF, on the other hand, are protracted and stretch from infancy across childhood until into adolescence (Best, Miller, & Naglieri, 2011; Huizinga et al., 2006; Van der Ven, Koroesbergen, Boom, & Leseman, 2011; Zelazo et al., in press; Zelazo & Carlson, 2012; Zelazo & Müller, 2002) with some EF components reaching maturity earlier (e.g., inhibition; Diamond, 2006).

1.4 EF as a Predictor of SA Performance

Attentional processes are usually regarded as domain-general processes and have previously been suggested to be a basic process for higher-order cognitive abilities (Garon, Bryson, & Smith, 2008; Reck & Hund, 2011; Steele et al., 2012; Wass, Scerif, & Johnson, in press; Zelazo, Carter, Reznik, & Frye, 1997). This assumption may be applicable for certain components of attention (e.g., focused attention, attentional shift); notably processes which, depending on the terminology, display similarities or may even be overlapping with EF components. However, it is questionable if the relationship is qualitatively different for the attentional component of SA. Based on the theoretical assumptions outlined above, it is thus conceivable that EF components, particularly inhibitory and working memory processes, may act as prerequisites for successful SA performance as the effective maintenance of attentional capacities over a longer period of time requires both inhibition (e.g., response to a distracting stimulus) and the storage of task demands (remembering the discriminative criteria of target objects opposed to distractors).

1.5 Aims of the Study and Hypotheses

The present study aimed at illuminating shared and unique processes of EF and SA; a question which is underrepresented in current literature. The age-dependent structure of EF components and SA were evaluated at first. We expected age-dependent performance differences in EF tasks as well as in the SA task. Moreover, an individual differences approach was applied by exploring the interrelations between EF and SA. We anticipated positive interrelations between the EF components (inhibition, switching, and working memory) and SA, indicating common underlying processes. Finally, we approached the question of whether distinct EF components predict individual differences in SA. Differential developmental improvements of the EF components may lead to a changing contribution of EF processes to SA with increasing age. This possibility was accounted for by evaluating the pattern of prediction within age-homogeneous subgroups with an age range of 1 year each.

2. Method

2.1 Participants

Participants were recruited in local schools in both urban and rural regions in different parts of Switzerland. Written parental consent was obtained for each child. 118 children aged between 5; 0 and 8; 11 completed the test battery (see Table 1 for demographic participant characteristics). Gender was distributed equally with 58 females (49.2%) and 60 males. 80.5% of the participating children had Swiss-German as their first language, while the remaining participants had sufficient language competencies to follow the instructions easily. In order to acknowledge assumed developmental differences in the assessed abilities, the sample was divided into four age-homogeneous subgroups (5-year-olds: 5; 0 to 5; 11, 6-year-olds: 6; 0 to 6; 11, 7-year-olds: 7; 0 to 7; 11, 8-year-olds 8; 0 to 8; 11).

2.2 Material

As for the domain of EF, tasks were selected theory-driven (Miyake et al., 2000). SA was assessed with a CPT (Brocki & Bohlin, 2004; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956), aiming at assessing attentional capacity in a monotonous and long-lasting situation with a low frequency of critical stimuli. Computer-based tasks were programmed and run using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) and were presented on a laptop. Responses (accuracies [ACC] and RT) were recorded employing a serial response box with two external response buttons, which were placed on the left and the right side next to the laptop keyboard. Descriptive data are provided for each task and age group separately in Table 1.

Table 1. Descriptives

	Age Group			
	5-year-olds	6-year-olds	7-year-olds	8-year-olds
N	29[a]	26[a]	33[a]	30[a]
Age in months, *M (SD)*	65.62 (3.6)	76.96 (3.53)	88.12 (3.33)	101.67 (3.35)
Females, *n* (%)	12 (41.4)	12 (46.2)	22 (66.7)	12 (40)
Inhibition				
Flanker inhibition composite score	5.47 (1.74)	7.39 (0.95)	7.76 (0.74)	8.59 (0.92)
Fruit/Vegetable Stroop interference score[b]	43.62 (14.45)	34.23 (8.19)	28.34 (9.67)	23.45 (8.97)
Switching				
aDCCS[c] composite score	5.09 (1.24)	5.44 (1.03)	5.46 (.76)	5.91 (0.84)
Cognitive Flexibility composite score	3.69 (1.63)	4.33 (1.82)	5.78 (1.14)	6.40 (1.11)
Working Memory				
Backward digit recall, trials	5.52 (2.76)	7.65 (2.15)	9.70 (3.58)	12.03 (3.03)
Backward color recall, trials	3.28 (2.37)	4.5 (2.34)	6.33 (1.88)	6.77 (1.72)
Sustained Attention				
CPT[d] sustained attention composite score	3.85 (2.30)	4.92 (1.61)	5.68 (1.31)	6.28 (1.97)

Note. Mean performance scores and standard deviations (in parantheses) are displayed for all EF measures separately as a function of age. [a] Degrees of freedom might be smaller for some tests as a consequence of pairwise exclusion due to outlying performance values; [b] Fruit/Vegetable Stroop interference scores are coded reversely; [c] aDCCS = advanced Dimensional Change Card Sort test; [d] CPT = continuous performance task.

Interrelations among the applied EF tasks were evaluated in order to create composite scores, consisting of test values within the EF components. As the sample consisted of a very broad age range, these correlations are likely to be inflated by differences which are attributable to developmental progression. Therefore, partial correlations were calculated with age being controlled for. Following theoretical assumptions explained above, we calculated intercorrelations among tasks within EF components (Flanker task and Fruit/Vegetable Stroop task for inhibition, aDCCS and Flexibility task for switching, and Backward digit recall and Backward color recall for working memory), and created EF composite scores, consisting of the sum of z-standardized test values within the respective EF component. EF composite scores were used for further analyses.

2.2.1 Inhibition

Inhibitory performance was assessed with a *Flanker* task (prepotent response inhibition) and with a *Fruit/Vegetable Stroop* task (interference control). In the Flanker task (adapted version of the Flanker task by Eriksen & Eriksen, 1974), the child was instructed to respond to a centrically presented stimulus (fish) irrespective of flanking stimuli (other fish; Roebers & Kauer, 2009). In order to establish a prepotent response, children completed one block, consisting of congruent stimuli (central fish with flanking fish aligned). Thereafter, two consecutive mixed blocks of congruent and incongruent stimuli (central fish with flanking fish opposed) were presented. 24 trials were carried out in each test block, (1/3 incongruent trials, 2/3 congruent trials) after an instruction trial and eight practice trials. Within a trial, an interstimulus interval (randomly varying between 800 and 1400 ms) was followed by a fixation cross (100 ms). Thereafter, the stimulus was presented for 1000 ms after another interstimulus interval (500 ms). As dependent variable, a Flanker inhibition composite score was calculated, consisting of RTs and ACCs of incongruent trials (Loher, Fatzer, & Roebers, 2012, based on the scoring algorithm applied by Zelazo et al., in press).

As for interference control, an adapted version of the Fruit Stroop task by Archibald & Kerns (1999) was applied (Roebers, Röthlisberger, Cimeli, Michel, & Neuenschwander, 2011). Four different pages, with five rows of five stimuli in each row were presented. On the first page, blue, green, red, and yellow squares were displayed. The child was instructed to name the colors as quickly as possible. On the second page, colored fruit and vegetables were depicted (blue plum, green salad, red strawberry, and yellow banana). The child was asked to name the colors of the fruit and vegetables. The next page consisted of the same fruit and vegetables, however, printed in black and white. In the final condition, the same fruit and vegetables were displayed in incongruent colors (e.g., blue banana) and the child's task was to name the original color of the fruit and vegetables (e.g., yellow for banana). As this condition requires the child to suppress the naming of the depicted colors and name the original and previously strengthened color instead, this condition is assumed to place highest demands on resistance to interference. The following interference score with time for completion was used as dependent variable: (page 4) – [(page 1*page 3) / (page 1 + page 3)] (Archibald & Kerns, 1999). Smaller scores were interpreted as reflecting higher abilities in resistance to stimulus-incompatibility (and thus enhanced performance in interference control).

Partial correlations (controlling for age) among inhibition tasks did not reach the level of significance (r_{age} = -.136, p = .15). However, following theoretical assumptions, an inhibition composite score was calculated nevertheless. The inhibition composite score consisted of the sum of z-standardized Flanker and (inverted) Fruit/Vegetable Stroop interference scores and was used for subsequent analyses.

2.2.2 Switching

The ability to flexibly switch between tasks was assessed with an *advanced Dimensional Change Card Sort* task (aDCCS), and the ability to switch between mental sets was tested with a *Cognitive Flexibility* task. In the current aDCCS task, bivalent stimuli (red square or blue circle) were presented centrically on the screen and the child was asked to respond according to one dimension (color or shape). Stimuli were incongruent in terms of the response dimensions (blue square and red circle). An external cue which was presented along with the stimulus reminded the child of the relevant response dimension. After two pure blocks (color first, shape thereafter or vice versa) with 14 trials each, a mixed block with unpredictable rule switches (referred to as task-switch trials) was conducted (46 trials). Sequence of pure blocks (color or shape first) was counterbalanced across participants. Within a trial, a fixation cross was presented for 500ms, followed by the stimulus which was presented along with the cue until a response ensued. As dependent variable, an aDCCS composite score (RTs and ACCs of task-switch trials) was calculated analogous to the flanker inhibition composite score (Loher, Fatzer, & Roebers, 2012; Zelazo et al., in press), reflecting the ability to successfully switch between tasks according to the current cue.

In the Cognitive Flexibility task, two representatives (fish) of different categories (unicolored vs. multicolored) were presented on a screen simultaneously; a unicolored fish on the one side and a multicolored fish on the other side (Roebers & Kauer, 2009). The child was instructed to feed the fish, steadily alternating between the unicolored and the multicolored fish. Therefore, the child had to change the response dimension trial after trial and thus had to continuously update the relevant response dimension (unicolored-multicolored) in order to press the correct button on the side of the target stimulus. The side of the presentation of the fish varied, following a predetermined, pseudo-randomized pattern with the target stimulus being presented on the left side of the screen in 48% of all trials. As the task encourages a predominant response set of changing response sides (left-right-left), non-switch trials referred to trials with changing response side (e.g., right-left) whereas trials with switching response sets (set-switch trials) were defined as trials with unchanging response sides in consecutive trials (e.g., left-left). After an instruction trial and 10 practice trials, two test blocks were conducted consisting of 23 trials each with a short break in between. Within a trial, the stimulus (unicolored and multicolored fish) was presented after an interstimulus interval varying randomly between 300 and 700 ms. The stimulus remained on the screen until the child responded. An auditory signal was presented if the child responded incorrectly. In the subsequent trial, the correct target stimulus was encircled. Since set-switch trials require the individual to abandon the previously established predominant response set, demands on switching performance are highest in this condition. A set-switching composite score was calculated as dependent variable. Consisting of RT and ACC of set-switch trials, this set-switch composite score was intended to reflect the child's ability to switch between mental sets according to the task demands.

Partial correlations (controlling for age) among both switching tasks showed to be significant ($r_{age} = .20$, $p = .04$). Even though this correlation coefficient has to be interpreted as small, a switching composite score, consisting of the sum of the z-standardized test scores of the aDCCS and Cognitive Flexibility task, was calculated following theoretical reasons. This switching composite score was used for further analyses.

2.2.3 Working Memory

Working memory was assessed with the *Backward digit recall* task of the Working Memory Test Battery for children (WMTB-C; Pickering & Gathercole, 2001) and a *backward color recall* task (Roebers, Schmid, & Roderer, 2010). In the Backward digit recall task, the child was presented with digits, which had to be memorized and repeated in the reverse order. After two practice trials, the task started with two digits (e.g., 2-7). Six trials were conducted in each span and span length was increased by one digit if the child remembered at least three trials correctly. Total number of trials correctly recalled backwards was used as dependent variable.

Similarly to the Backward digit recall, presented objects had to be remembered in the reverse order in the backward color recall (Neuenschwander, Röthlisberger, Cimeli, & Roebers, 2012). However, while the objects in the Backward digit recall were presented orally, colored discs (bisyllabic colors) were presented visually in the Backward color recall task. Three trials were conducted per span. The task started with a span length of two discs after three practice trials and was increased by one if the child scored at least two out of three correctly. Stimuli were presented for 1200 ms, separated by an interstimulus interval of 500 ms. In the end of the trial, a dwarf was presented as a retrieval cue until the child responded. Total number of discs recalled in the correct order backwards served as dependent variable.

Partial correlations with age being controlled for, revealed a statistically reliable correlation between the performance in the Backward digit recall and the Backward color recall ($r_{age} = .35$, $p < .001$). Therefore, a working memory composite score was calculated, consisting of the sum of z-standardized task scores of the backward digit recall and the backward color recall tasks, and was used for subsequent analyses.

2.2.4 Sustained Attention

For the assessment of SA, a CPT (Brocki & Bohlin, 2004; Rosvold et al., 1956) was applied. Thereby, the child had to respond to a critical yet infrequent cue-target combination (shark [cue], sad diver [target]) while ignoring distractors and noncue-target or cue-nontarget combinations. After 10 instruction and practice trials, children had to perform 100 test trials. Thereof, 25 trials were critical cue-target combinations. In additional 10 trials, the cue was presented but not followed by the target. In 10 trials, the target was displayed without the preceding presentation of the cue and thus not requiring a response. In further 15 trials, a stimulus was presented which was similar to the target on a perceptional level (nontarget). In another 15 trials, a distractor was presented, bearing contentual resemblance to the cue (noncue). Trial order was predetermined yet pseudo-randomized initially. Within a trial, an interstimulus interval (varying randomly between 2550 ms and 2775 ms) was followed by the stimulus (presented for 460 ms). As both latency and variability of responses have been suggested as valuable indicators of SA (see Betts et al., 2006), a SA composite score consisting of both mean RT and RT variability (SD) was used as dependent variable. In order to examine attentional performance in the course of the task (e.g., performance deterioration in the second half of the task), split-half reliabilities were calculated. As these reliabilities proved to be high ($r = .72$, $p < .001$), all trials were included with equal weight in the SA composite score.

2.2.5 Speed of Information Processing

As a control variable, speed of information processing was assessed with a computerized *Reaction Time* task (Kail, 1991; Loher et al., 2012; Roebers & Kauer, 2009). The child was instructed to respond as quickly as possible to a centrically presented stimulus (fish and fisherman). 16 test trials were conducted after six practice trials. In the run of a trial, the stimulus was presented for 1500 ms, and followed by an interstimulus interval, varying randomly between 1100 ms and 2500 ms. Mean RT was used as dependent variable. As the pattern of correlations between EF and SA did not change when entering RT as a covariate, RT was not included in the final analyses for the sake of simplicity.

2.3 Procedure

In order to prevent effects of fatigue, the assessment session was divided in two parts with an approximate duration of 30 minutes each. These sub-sessions were conducted in a separate and quiet room in the facilities of schools and kindergartens during morning hours on two different days. Two test battery versions were created with task order among these two versions being counterbalanced except for the SA task which was conducted as the very last task in order to assess attentional capacities after extended performance of cognitive effortful tasks. These two versions of the test battery were distributed equally among participants. After completion of all tasks, children received a little present.

3. Results

3.1 Statistics and Data Analysis

In order to exclude reactions not reflecting a task-relevant response, single trials with RTs exceeding the intra-individual mean by more than 3 SDs were excluded and only the remaining trial scores were used for the calculation of the mean RT. As this procedure only depends on intra-individual variation in speed of processing, these very slow responses are likely to reflect lapses of attention rather than intended responses to the presented stimulus. In terms of inter-individual outliers, dependent variables of the tasks were z-standardized for each age-group separately. Scores lower than 3 SDs of the mean of the age-group were excluded (concerning three single test scores of different individuals). As there were thus only very few missing values, pairwise exclusion was realized for statistical procedures, resulting in slightly varying degrees of freedom among the tasks.

3.2 Age-Dependent Performance Differences in EF Components and SA

As a potential indicator of an ongoing process of development between 5-year-olds and 8-year-olds, age-dependent performance differences within each EF component and SA were calculated, aiming at examining the tasks' sensitivity. Therefore, an analysis of variance (ANOVA) was calculated for each EF component and additionally for SA with age group as a between-subject factor (5-year-olds, 6-year-olds, 7-year-olds, and 8-year-olds). As homogeneity of population variances was not given for the EF component of switching, all post-hoc comparisons were obtained by means of the Games-Howell test. Partial eta^2- values (η_p^2) are reported as an estimation of the effect size. As for the component of inhibition (see Figure 1), a significant main effect of age group was detected, $F(3, 111) = 46.37$, $p < .001$, $\eta_p^2 = .56$. Post-hoc comparisons revealed significant performance differences among all age groups (5-year-olds < 6-year-olds < 7-year-olds < 8-year-olds). Thus, developmental progression in the component of inhibition seems to continue until at least almost 9 years of age, indicating good sensitivity of the applied tasks.

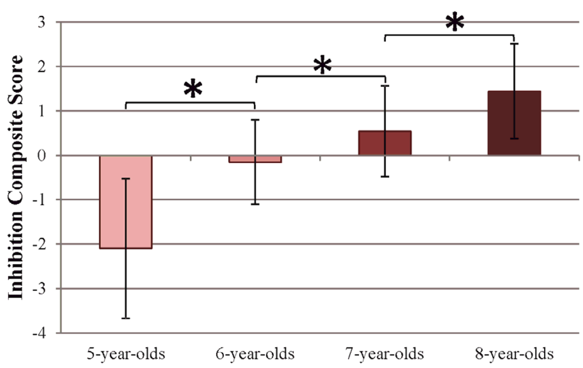

Figure 1. Inhibition

Note. Inhibition Composite Score, consisting of the sum of z-standardized Flanker inhibition composite scores and (inverted) Fruit/Vegetable Stroop interference scores. Means and standard deviations are displayed. * p< .05

For the EF component of switching, as can be seen in Figure 2, a main effect of age was discovered, $F(3, 109) = 17.06$, $p < .001$, $\eta_p^2 = .32$. Post-hoc comparisons showed significant performance differences between the 5-year-olds and the 7-year-olds and older. The 6-year-olds only differed significantly from the 8-year-olds. The 9-year-olds in turn differed significantly from all lower age groups.

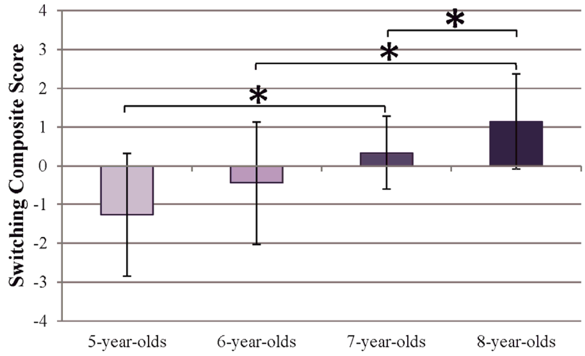

Figure 2. Switching

Note. Switching Composite Score, consisting of the sum of z-standardized aDCCS and Cognitive Flexibility composite scores. Means and standard deviations are displayed. * p< .05

As for working memory (depicted in Figure 3), again, a significant main effect of age group was found, $F(3, 114) = 31.30$, $p < .001$, $\eta_p^2 = .45$. Post-hoc comparisons revealed statistically reliable performance differences among the three younger age groups (5-year-olds < 6-year-olds < 7-year-olds). In contrast, the difference between the 7-year-olds and the 8-year-olds was not significant ($p = .08$).

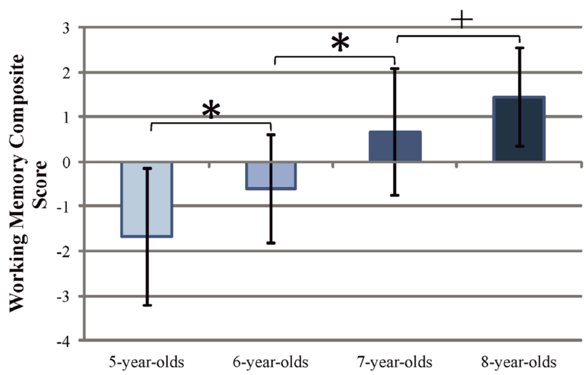

Figure 3. Working memory

Note. Working Memory Composite Score, consisting of the sum of z-standardized test scores in the Backward digit recall task and Backward color recall task. Means and standard deviations are displayed. * p< .05; + p< .1

Concerning the attentional component of SA (see Figure 4), a significant main effect of age group was revealed, $F(3, 113) = 9.67$, $p < .001$, $\eta_p^2 = .20$. Post-hoc comparisons of means showed reliable differences between the 5-year-olds and the 7-year-olds and older. The 6-year-olds only differed significantly from the 8-year-olds. The performance difference between the 7- and the 8- year-olds, despite being visible on a descriptive level, did not reach statistical significance.

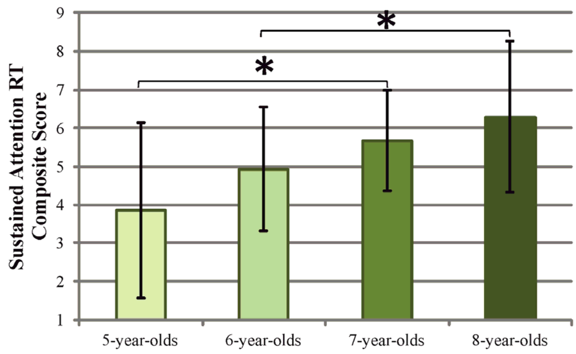

Figure 4. Sustained attention

Note. Sustained Attention Composite Score, consisting of the sum of z-standardized Mean CPT RT and CPT RT standard deviation. Means and standard deviations are displayed.

3.3 Interrelations between EF Components and SA

Next, the relation between EF and SA was examined by means of correlation analyses between the EF components and SA performance. Partial correlations controlling for age in months revealed substantial correlations between inhibition and SA (r = .31, p = .001), between switching and SA (r = .24, p = .01), and between working memory and SA (r = .26, p = .005). These results thus indicate small proportions of shared variance between all EF components and SA performance when age is controlled for.

3.4 EF Components as Predictors of SA Performance

In a final step of the analyses and with the aim of exploring unique contributions of EF components to SA performance, stepwise linear regression analyses with single EF components as individual predictors of SA performance were carried out. In order to acknowledge potential developmental differences in the pattern of predictability, regression analyses were calculated within the above-mentioned age groups of 12 months each separately. Controlling for gender did not change the results and was therefore omitted in the final analyses for the sake of clarity. As can be seen in Table 2, the regression analyses revealed different patterns of prediction, depending on the age group.

In the youngest age group (5-year-olds), the EF component of inhibition uniquely explained 19% of the variance in SA performance. Surprisingly, neither of the assessed EF components explained substantial amounts of variance in the 6-year-olds and the 7-year-olds. In the oldest age group (8-year-olds), in contrast, 32% of the variance in the SA task was explained by performance in the EF component of switching. As these results show, distinct EF components seemed to be predictive for individual differences in SA performance at certain time frames in the course of development. However, the pattern of predictors surprisingly varied substantially as a function of age.

Table 2. Linear Regression analyses

	5;0 to 5;11			6;0 to 6;11			7;0 to 7;11			8;0 to 8;11		
	B	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Inhibition	0.64	0.27	**.44***			.30$^{ns.}$			.25$^{ns.}$			-.04$^{ns.}$
Switching			.23$^{ns.}$			-.02$^{ns.}$			-.01$^{ns.}$	0.91	0.25	**.57****
Working Memory			.26^{ns}			-.08$^{ns.}$			.06$^{ns.}$			.03$^{ns.}$
n	27			24			32			30		
Total R^2	0.19									0.32		

Note. Stepwise regression analyses, calculated separately for each age group. ** p < .01; * p < .05

4. Discussion

The present study investigated the relation between EF components and SA. Results indicated age-dependent differences in the EF components of inhibition and working memory until at least the age of 8. No indication of ceiling performance in either age group suggests ongoing developmental progression. These findings point to a pronounced sensitivity of applied tests, particularly in the EF components of working memory and inhibition. Importantly, despite not being directly comparable due to the assessment by different tasks and metrics, these similar patterns of age-dependent improvements of performance may suggest common underlying processes in EF and in SA. Alternatively, an independent factor may fuel development in both EF and SA concurrently with parental behavior, or, more broadly family environment, potentially accounting for shared variance in EF and SA (Graziano, Calkins, & Keane, 2011; Razza, Martin, & Brooks-Gunn, 2010). In any case, results may thus be interpreted as indicating an ongoing yet probably not linear development in both the EF components and SA until almost 9 years of age. Our results of age-dependent performance differences are by and large compatible with the existing literature documenting performance improvements in all EF components and SA proceeding at least until the age of 7 (Best et al., 2011; Diamond, 2006; Klenberg et al., 2001; Van der Ven et al., 2011). The question of whether these only marginally differing performance trajectories in EF may be reflected in different patterns of explanation of variance in SA will be discussed later.

The proposition of an interplay of concurrently developing underlying processes driving performance in a SA task has been put forward by Steele and colleagues (2012), who called for empirical investigations of these interrelations. In the present study, such interrelations were found between EF components and SA. Differential interrelations were found between EF and SA, depending on the EF component considered, when age was controlled for. While the interrelations between switching and SA and working memory and SA showed to be statistically reliable yet weak, stronger relations were found between inhibition and SA. This pattern of results may be interpreted as pointing to common underlying processes, some of which are outlined and discussed in these paragraphs.

The question of whether the performance in EF components may predict variance in SA performance revealed an unexpected pattern of results. While inhibition explained a substantial amount of variance in the youngest age group (19% in 5-year-olds), no variance could be explained in SA with individual differences in EF performance in both middle age groups (6- and 7-year-olds). However, as much as 32% of the variance in SA performance was accounted for by only one variable, with this variable being switching performance in 8-year-olds. These findings of profoundly diverging patterns of explained variance among age groups suggest that EF components may underlie SA performance to some extent but that this influence changes in the course of development. At the same time, our results obviously show that SA and EF are clearly separable cognitive processes.

One possible answer to the question of the shift from inhibition uniquely explaining variance in SA performance in 5-year-olds to switching uniquely explaining variance in SA performance in 8-year-olds may be found in the different frames of development of the EF components combined with the increase of complexity in involved processes. Inhibitory components are assumed to start to develop substantially already early in ontogeny (Diamond, 2006; Klenberg et al., 2001). Therefore, it might be the case that in children as young as 5 years of age, the execution of more complex or enduring tasks may rely on inhibitory processes as they display an advanced level of development.

As an explanation of switching uniquely accounting for considerable amounts of variance in SA performance of 8-year-olds, arguments of the Cognitive Complexity and Control (CCC) theory (Zelazo & Frye, 1998) may be employed. According to this theory, developmental progression is reflected in an increase in complexity of represented rule structures. As one might argue, the age-dependent pattern of results thus indicates that this complexity of representations is required to execute switching tasks as they face the individual with a high degree of complexity and prerequisite the orchestration of lower-level processes (Zelazo et al., 2008). However, once this level of complexity of representations is achieved, it may be crucial for the execution of highly demanding tasks. As the SA task in our study requires the child to maintain the task rule in a two-step-sequence of a critical cue-target combination (if shark *and* sad diver then reaction), our SA task may be considered as a task of high load (Betts et al., 2006). Therefore, both age-dependent SA improvement and diverging patterns of explained variance could potentially be associated with incrementing complexity of representations across development.

4.1 Limitations and Implications for Future Studies

There are several limitations and implications for further studies that ought to be mentioned at this point. First, due to our cross-sectional design, our results are certainly not indicative of any causal relations between EF and

SA. In order to approach the depiction of causal relations, longitudinal designs should be considered in future studies. Second, as we did not include external criteria, it was not possible to illuminate additional factors, which may explain further proportions of variance (e.g., intelligence, parental behavior, temperament, emotion regulation). Our strictly cognitive attempt of explanation may thus not be adequate for SA and future studies may possibly include additional social and emotional variables in order to help to explain additional variance in SA performance. Third, our sample size, particularly after dividing into age-homogeneous groups, was relatively small for conducting regression analyses, attenuating our interpretations and calling for a replication of our results within a larger sample. Fourth, in the present study, we assessed overt SA performance, as it is displayed in a CPT. One might wonder, whether interrelations would be stronger or, in contrast, weaker, if measures of covert attentional capacity (e.g., eye movements) would be considered. As an additional advantage, the inclusion of measurements of covert attentional capacities may allow a more ecologically valid assessment of SA. Fifth, as our study is considered as basic research, and thus contributing to the fundamental knowledge of similarities and differences between EF and SA, a direct application in classrooms is not possible. The assessment of external variables is therefore of utmost importance in future studies in order to estimate the common contribution of EF and SA to school-relevant factors such as academic achievement or learning related behavior.

4.2 Conclusions

To conclude, we attempted to compare and differentiate the construct of EF with the attentional component of SA. Despite suggested similarities in the pattern of age-dependent performance differences among EF components and SA and small yet significant interrelations among single EF components and SA, explanatory power of SA performance by EF components was found to be limited. Differential patterns of explained variance were found across age groups. This finding was discussed as an indicator of a clear discriminability of SA and EF, and as a potential mirror of developmental trajectories of underlying EF processes. However, it still leaves a margin for further factors contributing to SA development.

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