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Dimensionality of executive functions and processing speed in preschoolers☆

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ABSTRACT

Processing speed is a foundational cognitive ability strongly associated with executive functions in children. To precisely interpret children's results in measures of executive functions, it is important to identify variation that is due to differences in executive functions versus processing speed. In this study, we examined the dimensionality of executive functions and processing speed in 3–6 years old preschoolers over six months with two time points. Executive functions and processing speed (i.e., choice reaction time) were assessed using computer-based tests.

Confirmatory factor analyses showed that executive functions and processing speed were divided into two dimensions (processing speed+inhibition+switching and updating) at both time points. Regarding executive functions, the findings indicate that in preschoolers, inhibition+switching is inseparable, but updating is separable from processing speed. Findings emphasize the need to critically evaluate the underlying characteristics of different executive function tasks to better understand the development of executive function and its associations with other cognitive and academic skills.

Educational relevance statement: In this study, we examined dimensionality of executive functions and processing speed in preschoolers. Executive functions have been identified as important predictors for school readiness and later academic performance. To better understand individual differences in executive functions and their associations with other cognitive and academic skills in early childhood, accurate measures of executive functions are needed. However, there has been concern that other cognitive processes involved in performing various EF tasks might mask variation in executive functions proficiency. Processing speed is one potential source of measurement impurity in measures of executive functions. However, the evidence about the dimensionality of executive functions and processing speed among young children is limited. To precisely interpret the children's results in measures of executive functions, it is important to identify variation that is due to differences in executive functions versus processing speed.

1. Introduction

Executive functions (EF) is an umbrella term for higher-order cognitive processes necessary for goal-directed behavior (Diamond, 2013). EF develop rapidly during the preschool years creating the foundation for the development of higher-order cognitive processes (Garon et al., 2008) and it has been identified as an important predictor for school readiness (e.g., Bull et al., 2008) and later academic performance (Cameron et al., 2012; Clark et al., 2010; Schmitt et al., 2017). Although the dimensionality of EF is widely studied (e.g., Lee et al., 2013), findings in younger children have been inconsistent (Espy et al., 2004; Monette et al., 2015; Wiebe et al., 2011.) In addition, there have been concerns that other cognitive processes (e.g., processing speed) may mask children's true EF proficiency (Miyake et al., 2000). The vast majority of previous studies examining these "task impurity" -issues have concentrated on school-aged children (McAuley & White, 2011; Rose et al., 2011; Span et al., 2004). Thus, the aim of this study was to examine the dimensionality of executive functions and processing speed

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in 3–6 years old preschoolers over six months with two time points.

2. Theoretical background

2.1. The dimensionality of executive functions in preschoolers

Three dimensions of EF have been described in the literature: Inhibition, updating and switching. Inhibition refers to the ability to prevent dominant, automatic or prepotent responses from interfering with the desired responses. Updating refers to the ability to monitor, refresh, and maintain relevant information in mind. Switching refers to the ability to move between multiple tasks, operations, or mental sets (Miyake et al., 2000). Most previous executive function studies have also used the concept of working memory that included the dimensions of working memory capacity and updating. Working memory capacity refers to the amount of information that can be held in mind for use in ongoing information processing (Panesi et al., 2022). Working memory capacity determines how much updating has to be done to process information. At the measurement level, these two constructs are closely related and are often difficult to separate. Therefore in this paper, we use the term "working memory/updating" to refer to the findings in previous studies that have used measures for working memory capacity and/or updating (e.g., Monette et al., 2015; Nelson et al., 2022). Three separate dimensions of EF have been reported in studies involving school-age children (Lehto et al., 2003) and young adults (Miyake et al., 2000). In preschoolers, earlier studies reported a three-factor structure (Espy et al., 2004; Hughes, 1998), but in all studies using confirmatory factor analyses, a one-factor structure (Fuhs & Day, 2011; Hughes et al., 2009; Wiebe et al., 2008; Wiebe et al., 2011) or a two-factor structure comprising inhibition and a factor comprising of switching and working memory/updating measures (Miller et al., 2012; Usai et al., 2014) have been found. In a recent longitudinal study by Nelson et al. (2022), a one-factor structure was found to fit best the data in preschoolers, while a two-factor solution with working memory/updating and an inhibition plus switching factors was the preferred model for school-aged children. There seems to be an age-related pattern in these findings as studies among three years old preschoolers have consistently reported an unidimensional structure (Fuhs & Day, 2011; Shing et al., 2010; Wiebe et al., 2008, 2011). Among older preschoolers one- (Hughes et al., 2009) and two-factor structures have been found (Miller et al., 2012; Monette et al., 2015; Usai et al., 2014).

2.2. The role of processing speed

One possible explanation for these conflicting findings regarding dimensionality of EF might be a methodological issue called "task impurity", which means that variation in EF performance is influenced by other cognitive processes (Miyake et al., 2000). Processing speed is one potential source of measurement impurity in measures of EF (Kail & Salthouse, 1994; Miyake et al., 2000). Processing speed is defined as an efficiency of information processing and it is a central mental capacity that enables changes in higher order cognition (i.e. EF; Kail & Salthouse, 1994). Processing speed has been found to increase rapidly in early and middle childhood, and the development continues until mid-to-late adolescence, leading to an enhanced capacity for manipulating information (Kail, 1991). Changes in processing speed has been found to explain age-related improvements from childhood to young adulthood in working memory/updating (Fry & Hale, 1996, 2000), switching (Salthouse et al., 1998) and inhibition (Christ et al., 2003; McAuley & White, 2011). These previous findings emphasize the importance of taking processing speed into account when interpreting the results of EF-studies.

Processing speed is measured by tasks that measure reaction time (Kail, 1991; Willoughby et al., 2020); that is the time interval between the presentation of a stimulus and responding to the stimulus. There are at least two types of reaction time measures: Simple reaction time and choice reaction time. In simple reaction time tasks, participants are typically asked to press a key as soon as they see a stimulus. In choice reaction time tasks, a decision needs to be made about some characteristics of the stimulus in addition to pressing the key as quickly as possible. In a few previous studies in preschoolers, a simple reaction time task in which children needed to touch the screen as fast as possible when a bubble was presented on the screen have been used to measure processing speed (Willoughby et al., 2020, 2018). In most previous studies in preschoolers, choice reaction time tasks have been used to measure processing speed. These tasks have included computer-based reaction time tasks in which children need to choose whether, for example, color, size or quantity presented on the screen are different or the same (Miller & Vernon, 1997) or visual matching in which children need to identify matching shapes or digits (Clark et al., 2014). In some studies, response times from simple conditions from EF tasks with minimal EF demands have been used as measures for processing speed (Clark et al., 2014; Lee et al., 2013; van der Ven et al., 2013).

In the present study, processing speed has been operationalized as choice reaction time as more processing of information is needed in these tasks than in simple reaction time tasks. In addition, this makes comparison with previous studies easier, as choice reaction time tasks have been used to measure processing speed in most previous studies in preschoolers (Clark et al., 2014;Lee et al., 2013 ; van der Ven et al., 2013).

2.3. Executive functions and processing speed

Confirmatory factor analysis (CFA) has been used to estimate the effects of underlying EF processes on performance in EF tasks (Miller et al., 2012; Wiebe et al., 2008, 2011). CFA computes a measure of EF processes as a latent factor with the influence of non-EF-related cognitive processes captured by an error term (Espy & Willoughby, 2016). Because CFA captures all common variance of indicators (Lee et al., 2013; Salthouse & Ferrer-Caja, 2003), non-executive cognitive processes (e.g., processing speed) that are common to all tasks used to measure EF are still present in the latent factors. Thus, even with a CFA approach, variation due to EF abilities versus processing speed are still conflated (van der Sluis et al., 2007). To combat this issue, some studies that examined the structure of EF added measures of processing speed to their models to attenuate this source of measurement impurity (Lee et al., 2013; van der Ven et al., 2013). In these studies, two-factor models comprising inhibition+switching and working memory/updating (Lee et al., 2013; van der Ven et al., 2013) were found to best describe the data in 6-years old children. In particular, inhibition and switching were found to be strongly associated with processing speed, suggesting that measures of inhibition and switching might reflect the same underlying cognitive resource as measures of processing speed in this age group.

Some previous studies have been particularly focused on investigating the dimensionality of EF and processing speed in various age groups (e.g., Clark et al., 2014; Rose et al., 2011). In school-aged children, processing speed and EF have been shown to be separate factors, but strongly associated (McAuley & White, 2011; Rose et al., 2011; Span et al., 2004). Rose et al. (2011) found that a four-factor model (inhibition, shifting, working memory/updating, processing speed) best described the data in 11-years old children, when compared to one- and two-factor models. They also found that the intercorrelations between EF-tasks dropped when processing speed was controlled in the model, indicating that processing speed is a common factor explaining the performance in EF tasks. McAuley and White (2011) constructed latent variables for processing speed, inhibition and working memory/updating and reported that a 3-factor model worked best over one factor or two-factor-model (processing speed- and EF-factor) in childhood to young adulthood (6–24 years of age).

Only a few studies have examined the association between EF and processing speed in 3- to 5-years old preschoolers. In a study by Willoughby et al. (2020), children aged 3–5 were measured three times within one academic year to test associations between processing speed and EF. The mean response time for correct trials in a simple reaction time task was used as an indicator of processing speed, and accuracy scores from six different tasks were used as indicators for EF (one for switching, three for inhibition, and two for working memory/updating). EF composite scores and processing speed were found to be associated at each measurement point ($r = -0.45$ to -0.51). The processing speed was found to be more strongly correlated with inhibitory control (-0.41 to -0.46) than with working memory ($r = 0.28$–0.38). These findings indicate that EF and processing speed are distinguishable, but are correlated with each other. However, the dimensionality of EF and processing speed was not tested with CFA. In Clark et al. (2014), CFA was used to test relations between processing speed and EF. In their study, response times for correct trials from five different tasks measuring choice reaction time were used as indicators for processing speed and accuracy scores from 13 tasks as indicators for EF (inhibition, switching and working memory/updating). They found that processing speed and EF were inseparable at ages 3 and 3.75 years, but distinguishable at ages 4.5 and 5.25 years, suggesting that processing speed and EF differentiate during preschool period (Clark et al., 2014).

These previous studies in preschoolers have used mean response times and accuracy as measures for EF and processing speed, but none of them has checked the structure separately by using the accuracy and response time from the same tasks, allowing to detect the effect of the measure used on dimensionality of EF and processing speed.

2.4. The present study

Previous studies have reported important findings related to the dimensionality of EF and processing speed in children. However, there are gaps in our knowledge related to children at a young age. Despite the mixed findings on the dimensionality of EF in early childhood (e.g., Fuhs & Day, 2011; Lee et al., 2013; Monette et al., 2015), different factor structures (e.g., unidimensional factor structure, separate factors for inhibition+switching and working memory/updating or separate factors for inhibition switching and working memory/updating) for EF have not been tested in previous studies that examined the association between EF and processing speed in preschoolers. Therefore, in the present study, the dimensionality of EF and processing speed was examined together. Furthermore, the vast majority of the previous studies examining the structure of EF have been cross-sectional or have focused on only a narrow age range. However, previous findings suggest that the structure of EF (Monette et al., 2015; Wiebe et al., 2011), and dimensionality of EF and processing speed (Clark et al., 2014) might change during the preschool years. Therefore, in the present study we covered a wider age range (3–6–years old) and examined whether dimensionality of EF varied in the same children between two time points.

In previous studies investigating the association between EF and processing speed in preschoolers (Clark et al., 2014; Willoughby et al., 2020), accuracy scores have been used to measure EF and response time to measure processing speed. However, different metrics (response time and accuracy scores) used to measure different constructs might influence the results (van der Ven et al., 2013). Using the response time as a measure may be problematic because of a trade-off between accuracy and reaction times, that is, children prioritize accuracy over speed of response or vice versa (Heitz, 2014). Therefore, in the present study, the main models using response times were reanalyzed using accuracy scores as measures for all indicators, to confirm that the findings are not due to metrics used.

The aim of this study was to examine the dimensionality of executive functions and processing speed in 3–6 years old preschoolers with two time points. Based on previous research we hypothesized that (H1) EF are divided into one or two components (Lee et al., 2013; Monette et al., 2015), and that (H2) processing speed can be separated from EF, albeit strongly associated in both time points (Clark et al., 2014; Willoughby et al., 2020).

3. Methods

3.1. Participants

This study was part of the xxxxx study with a total of 303 participants. The participants were recruited from 15 preschools in the metropolitan area of Finland in October 2019. Of these children, 212 participated at both time points and 91 additional children were only tested at time point two. All of the children participated in the EF and processing speed measurements. Due to Covid-19, we could not collect as much data in T1 as we had planned. This explains the difference between the total amount of data for T1 ($n = 212$) and T2 ($n = 303$). Data were included in the analyses if children had valid data on at least one of the tasks in both time points. After data cleaning, there was valid data for 182 children. As not all the children had data for each task, the number of valid cases ranged from 146 to 178 between different conditions. The mean age of the children were 4.8 ($SD = 0.6$, range: 3.7–6.4) years in time point one and 5.3 ($SD = 0.6$, range: 3.9–6.9) years in time point two. Parents filled in a consent form where they gave permission for children to participate in the study. Parents were required to ask children for oral permission to participate in the study. Children were informed that participation was voluntary. The University's ethics committee approved the study protocol.

3.2. Study protocol

Data were collected across two time points between August 2020 and November 2021. The time between measurements was planned to be a maximum of six months, but due to the COVID19-outbreak, the time between the measurement points varied from one month to 14 months ($M = 6.6$; $SD = 2.7$). EF and choice reaction time were assessed by using four computer-based tests programmed using the ePrime software. The assessments were conducted individually in a quiet room during preschool hours and were divided into two approximately 20-min test sessions. Trained assistants performed all the tasks.

3.3. Tasks to measure EF and choice reaction time

The Flanker, Simon and Mickey inhibition task were used to assess inhibition, switching and choice reaction time (Lee et al., 2013). In the Flanker task, first a single fish (neutral trial) and then a row of five fish were presented on the screen and children were asked to identify the direction of the middle fish by pressing the keyboard button pointing in the same direction as the fish on the screen. There were arrow buttons on the keyboard pointing to the left and to the right. The fish in the middle was facing in either the same (congruent trial) or the opposite direction (incongruent trial) than all the other fish. On each trial first, a fixation cross was first presented at the center of the screen, and was after 750 ms replaced directly by the presentation of the stimulus for 3250 ms. There was first a block of 20 neutral trials followed by blocks of 20 congruent trials and 20 incongruent trials. These were followed by three blocks of 28 trials, in which congruent and incongruent trials were mixed. Mean response times from correct responses in four different conditions (congruent, incongruent, switch and no-switch) were used as dependent measures. Congruent and incongruent conditions included tasks from pure blocks of incongruent and congruent trials. Switch condition included tasks from mixed blocks involving conditional switches (incongruent-congruent or congruent-incongruent). Response times from incongruent conditions were used as indicators for inhibition, and response times from switch conditions for switching. Congruent and no-switch conditions were used as indicators for choice reaction time. The Cronbach's alpha values for the Flanker task in time point one and two were 0.72 and 0.65 for the congruent, 0.87 and 0.87 for the incongruent, 0.92 and 0.91 for the no-switch, and 0.86 and 0.86 for the switch trials, respectively.

In the Simon task, a butterfly or a frog were presented on the left or the right side of a computer screen. Children were instructed to take the butterfly and the frog home as quickly as possible by pressing a button with a picture of the corresponding animal. There was a picture of the butterfly on the left side and a picture of a frog on the right side of the keyboard. The pictures were presented either on the same side (congruent trial) or on the opposite side (incongruent trial) as the button with the picture of the corresponding animal. On each trial, a fixation cross was first presented for 750 ms at the center of the screen, followed by the presentation of the stimulus for 2500 ms on either side of the fixation cross. Children were administered a block of 25 incongruent trials followed by another block of 25 congruent trials. These two pure incongruent and congruent blocks were followed by four blocks of 21 trials, in which congruent and incongruent tasks were mixed. Mean response times from correct responses in four different conditions (congruent, incongruent, switch and no-switch) were used as dependent measures. Congruent and incongruent conditions included tasks from pure blocks of incongruent and congruent trials. Switch condition included tasks from mixed blocks involving conditional switches (incongruent-congruent or congruent-incongruent). Response times from incongruent conditions were used as indicators for inhibition, and response times from switch conditions for switching. Congruent and no-switch conditions were used as indicators for choice reaction time. The Cronbach's alpha values for the Simon task in time point one and two were 0.97 and 0.68 for the congruent, 0.97 and 0.73 for the incongruent, 0.97 and 0.71 for the no-switch, and 0.96 and 0.65 for the switch trials, respectively.

In the Mickey inhibition task, children were first instructed to look at a fixation point at the middle of the screen. After 750 ms, the fixation point disappeared, and white squares flashed on both or either side of the screen. After 200 ms, a picture of Mickey Mouse appeared on the same (congruent trial) or the opposite side (incongruent) of the screen as the white square. The presentation time of the stimulus was 2000 ms. In the neutral trials, white squares flashed on both sides of the screen. There were buttons with pictures of the Mickey Mouse on the left side and on the right side of the keyboard and children were asked to press the button on the same side as the Mickey on the screen as quickly as possible. The first block of 26 trials included congruent and neutral conditions followed by a block of 26 trials including incongruent and neutral trials. Finally, there were four blocks of 13 trials that contained congruent, incongruent and neutral trials. In total, there were 36 neutral, 35 congruent, and 33 incongruent trials. Congruent and incongruent trials were used in the analyses. Response times from incongruent conditions were used as indicators for inhibition, and from congruent conditions as indicators for choice reaction time. The Cronbach's alpha values for the Mickey inhibition task in time point one and two were 0.63 and 0.63 for the congruent, and 0.98 and 0.66 for the incongruent trials, respectively.

Updating were assessed by the pictorial updating task (Lee et al., 2013). In this task, a varying number of animal pictures (two to six) were shown one at a time on the computer screen. Children were asked to recall a specified number (1 to 3) of animals that were presented last on the screen. Pictures of all animals were presented on the screen and children were asked to select the correct animals by pressing the pictures on the screen in the same order as they had been presented. The presentation time of each animal was 1900 ms and there were 100 ms between presentations of the animals. There were three blocks with six trials in each. Children had to recall: one animal in the first block, two animals in the second block and three animals in the third block. The number of animals presented in each trial varied from two to four in the first block, three to five in the second block and four to six in the third block. One point was given for each animal recalled in the same order as presented on the screen. In the pictorial updating, the accuracy scores were used as dependent measures. The Cronbach's alpha value for the pictorial updating task was 0.78 in time point one and 0.83 in time point two.

In all tasks, the test instructions were read aloud to the children before each block of the task. In the beginning of each block, there were practice trials, in which children received feedback on their performance. In the Flanker, Simon and Mickey tasks, children were instructed to keep the fingers on the response buttons during the tasks.

In the Flanker, Simon, and Mickey tasks, the first four trials of each block were excluded from the analyses to allow responses to stabilize. Congruent and no-switch conditions were used as indicators for choice reaction time as these were counterparts for more EF demanding incongruent and switch conditions and represented ability to respond quickly to stimulus. These tasks were classified as measures of choice reaction time as there were two possible responses and demanded simple decision-making. A total of 156 trials for processing speed, 70 trials for inhibition, 56 trials for switching and 36 trials for updating were used in analysis.

3.4. Data analysis

Data from two measurement points were analyzed separately with similar methods. Missing values, outliers, and normality of distribution were screened separately with data from various conditions. Data from the Flanker, the Simon and the Mickey tasks were first cleaned at the subject level by using trial-by-trial response time data from each condition. Response time data were included in the analyses only if there were at least seven correct responses in a congruent block in each test and 75 % of correct responses in each condition. Response times that differed by >3 SDs from the individual mean in each condition were deleted. In all trials, response times of <250 ms were treated as anticipatory responses and were deleted.

After cleaning the data at the subject level, mean response times were calculated for each condition. In the next phase, mean response times that differed by >3 SD from the group mean were replaced by values at 3 SD resulting in replacement of 39 values. This affected 1.01 % of the data. The response times after cleaning procedure in each condition were used in further analyses. In the animal updating task, no accuracy scores that differ by >3 SD from the mean were found.

Preliminary analysis was conducted with SPSS software (Version 28; IBM statistics). Means, SDs and values of skewness and kurtosis were calculated for each task. Differences in choice response times between congruent and incongruent (inhibitory cost), and between switch and no-switch (switch cost) tasks were tested using paired sample *t*-test. For the main analyses, age-controlled variables were constructed by regressing age on test scores and by saving standardized residuals of the regression as new variables. The main analyses were conducted using Mplus version 8.6 (Muthen & Muthen, 1998–2004). The dimensionality of EF and choice reaction time were tested using the confirmatory factor analysis (CFA).

In line with a three factor model by Miyake et al. (2000), inhibition, switching and updating factors were constructed. The inhibition factor was indicated by measures from the incongruent conditions from the Flanker, Simon and Mickey Inhibition tasks. The switch factor was indicated by corresponding measures from the switch conditions. Congruent and no-switch conditions from The Flanker, Simon and Mickey Inhibition tasks were used to construct a choice reaction time factor. To construct a latent variable for updating, the animal updating task was split into three parcels. Parcels were created by summing the number of correct responses of every third item of the task (i.e., parcel1: item1, item4…;parcel2: item2, item5…& parcel3: item3, item6…).

Five different CFA-models were constructed: The one-factor model consisted of a single latent factor including all conditions; the two-factor model specified separate latent factors of choice reaction time and inhibition+switching+updating; the first three-factor model specified separate latent factors of choice reaction time, inhibition+switching, and updating; the second three-factor model specified separate latent factors of choice reaction time, inhibition, and updating+switching; and the four-factor model specified separate factors for choice reaction time, inhibition, switching and updating.

One-factor model was based on the hypothesis that EF and choice reaction time are inseparable (Clark et al., 2014). Other three models were based on the assumption that EF and choice reaction time are separable factors (McAuley & White, 2011). In these models, different structures for EF and associations of different components of EF with choice reaction time were tested as one- (Fuhs & Day, 2011; Wiebe et al., 2008, 2011), two- (Lee et al., 2013; Monette et al., 2015) and three-factor (Espy et al., 2004) structures for EF have been reported in preschoolers.

Maximum likelihood estimator was used and residual variances of indicators were allowed to correlate within the task in all analyses. The comparative Fit Index (CFI; cut-off values close to >0.9), Tucker Lewis Index (TLI > 0.9), Root Mean Square Error of Approximation (RMSEA < 0.08) and maximum likelihood (ML) -based standardized root mean squared residual (SRMR < 0.06) were used as criteria for good model fit (Hu & Bentler, 1999; Marsh et al., 2004).

CFA-models were compared with one another using the chi- square difference test. The chi-square values and degrees of freedom of the less restrictive model were subtracted from the chi-square value and degrees of freedom of the more restrictive model. The significance of the difference was then tested by comparing the chi-square difference value to the chi-square value in a chi-square table using the difference in degrees of freedom. A significant difference indicates that a less restrictive model provides a significantly better fit.

4. Results

4.1. Preliminary analysis

Data were screened for missing values, outliers, and normality of distribution. Descriptive statistics for each condition in both time points are presented in Table 1. Overall, the mean response times in all conditions were faster in time point two compared to time point one. In the pictorial updating task, children tended to recall more animals in time point two than in time point one. In the Simon task, response times were slowest in the switch tasks and the fastest in the congruent tasks in both time points. Children tended to respond faster in the choice reaction time tasks (congruent and no-switch tasks) compared to inhibition and switch tasks (incongruent and switch tasks) in both time points. In the Flanker task, response times were slowest in the incongruent tasks and fastest in the congruent tasks in both time points. Children responded faster in the switch tasks compared to no-switch tasks in time point one, but in time point two responses were faster in no-switch tasks compared to switch tasks. In the Mickey task, responses were faster in the congruent than the incongruent tasks in both time points.

As a preliminary analysis to test the assumption that response times are slower in indicators for EF and faster in indicators for choice reaction time, differences were tested using paired sample *t*-test. As shown in Table 2, differences in response times were found to be significant in all pairs of conditions except for the Flanker switching and no-switching tasks at time point one. Therefore, the Flanker switch and no-switch tasks were excluded from further analysis in time point one. To make comparison possible between time points, exclusion was also made in time point two. Because the Simon switch was left as the only indicator for the switching factor, it was split into three parcels with each formed by data from every third item (Table 3). The models tested in CFA have been presented in Fig. 1.

4.2. The dimensionality of executive functions and choice reaction time at time point one

Five different models were constructed using CFA (Fig. 1). As shown in Table 4 the goodness-of-fit indices showed that the three-factor model (choice reaction time, inhibition+switching and updating) and four-factor model were the only models with acceptable model fit in both time points. In these models all indicators had acceptable factor loadings.

Chi-square difference test showed that there were statistically significant improvements in model fit when the three-factor structure was fractionated into four factors. This indicates that the four-factor model should be retained over the three-factor model. However, there were very strong associations between inhibition and switching (r = 0.939,

Table 1
Descriptive statistics for each variable in time point one and time point two.

	Time point 1							Time point 2						
		Response time			Accuracy				Response time			Accuracy		
Task	N	M (SD)	Skew.	Kurt.	M (SD)	Skew.	Kurt.	N	M (SD)	Skew.	Kurt.	M (SD)	Skew.	Kurt.
The Flanker Congruent	161	1241 (309)	0.384	−0.488	14.7 (1.2)	−0.887	0.020	177	1037 (296)	0.588	−0.248	14.9 (1.1)	−0.658	−0.574
The Flanker Incongruent	129	1558 (366)	−0.130	−0.469	12.8 (2.7)	−0.673	−0.641	164	1313 (423)	0.470	−0.232	13.4 (2.7)	−1.109	−0.054
The Flanker No-Switch	161	1443 (315)	0.322	−0.153	37.4 (8.0)	−0.649	−0.711	177	1208 (341)	0.693	0.465	39.7 (7.6)	−1.369	0.921
The Flanker Switch	160	1457 (349)	0.408	−0.041	18.2 (4.6)	−0.554	−0.907	176	1254 (384)	0.648	0.029	20.0 (4.2)	−1.193	0.312
The Simon Congruent	153	918 (322)	1.511	2.252	19.7 (1.4)	−0.943	0.038	170	820 (266)	0.957	0.354	19.8 (1.3)	−1.072	0.698
The Simon Incongruent	153	1072 (257)	1.015	1.539	19.5 (1.6)	−1.491	2.603	170	972 (233)	0.763	−0.048	19.4 (1.7)	−1.278	1.683
The Simon No-Switch	153	1122 (262)	0.980	0.698	32.1 (2.9)	−1.166	1.454	170	1039 (231)	0.780	0.345	32.4 (3.0)	−1.277	1.685
The Simon Switch	153	1210 (261)	1.003	1.479	27.3 (3.0)	−0.766	0.068	170	1138 (238)	0.808	0.940	27.5 (3.0)	−1.098	1.475
The Mickey Congruent	146	846 (226)	1.184	0.811	32.3 (2.0)	−0.801	0.166	163	767 (206)	1.055	0.941	32.8 (2.0)	−1.303	1.872
The Mickey Incongruent	146	918 (262)	1.234	1.013	30.1 (2.3)	−1.215	1.433	163	836 (227)	1.095	0.805	30.6 (2.2)	−1.473	3.244
The Pictorial Updating, Parcel 1	178	3.3 (1.9)	0.387	−0.262	3.3 (1.9)	0.387	−0.262	175	4.2 (2.1)	0.329	−0.115	4.2 (2.1)	0.329	−0.115
The Pictorial updating, Parcel 2	178	3.5 (1.9)	0.123	−0.273	3.5 (1.9)	0.123	−0.273	175	4.3 (2.1)	0.211	−0.339	4.3 (2.1)	0.211	−0.339
The Pictorial Updating, Parcel 3	178	3.9 (2.3)	0.533	−0.477	3.9 (2.3)	0.533	−0.477	175	5.0 (2.6)	0.004	−0.482	5.0 (2.6)	0.004	−0.482

Table 2
Comparison of response times in measures for executive functions and choice reaction time.

	Time point 1				Time point 2					
	M_{diff}	SD_{diff}	t	p	Cohen's D	M_{diff}	SD	t	p	Cohen's D
Fc-Fi	−372.086	329.991	−12.807	<0.001	−1.128	−296.534	317.984	−11.942	<0.001	−0.933
Fns-Fs	−13.991	174.361	−1.015	0.312	−0.080	−47.073	152.099	−4.106	<0.001	−0.309
Dc-Di	−154.769	242.428	−7.897	<0.001	−0.638	−152.331	172.303	−11.527	<0.001	−0.884
Dns-Ds	−87.601	112.207	−9.657	<0.001	−0.781	−98.389	105.482	−12.162	<0.001	−0.933
Mc-Mi	−71.300	97.294	−8.855	<0.001	−0.733	−69.265	88.488	−9.994	<0.001	−0.783

Note. Fc = The flanker congruent tasks, Fi = The flanker incongruent tasks, Fns = The flanker no-switch tasks, Fs = The flanker switch tasks, Sc = The Simon congruent tasks, Si = The Simon incongruent tasks, Ss = The Simon switch tasks, Sns = The Simon no-switch tasks, Mc = The Mickey congruent tasks, Mi = The Mickey incongruent task.

Table 3
Descriptive statistics for The Simon switch parcels in both time points.

	Time point 1							Time point 2						
		Response time			Accuracy				Response time			Accuracy		
Task	N	M (SD)	Skew.	Kurt.	M (SD)	Skew.	Kurt.	N	M (SD)	Skew.	Kurt.	M (SD)	Skew.	Kurt.
The Simon switch, parcel 1	153	1206 (274)	1.151	2.353	9.4 (1.2)	−0.300	−0.636	170	1140 (256)	1.101	1.806	9.3 (1.5)	−0.917	−0.521
The Simon switch, parcel 2	153	1206 (261)	0.821	0.807	9.5 (1.4)	−1.019	0.845	170	1125 (248)	0.611	0.006	9.7 (1.4)	−1.355	1.902
The Simon switch, parcel 3	153	1212 (288)	0.883	0.889	8.5 (1.4)	−1.187	1.502	170	1158 (279)	0.978	1.326	8.5 (1.4)	−1.013	0.803

95 % CI [0.881, 0.996], p < .001), and between choice reaction time and switching (r = 0.956, 95 % CI [0.926, 0.987], p < .001) in the four-factor model (Fig. 2). The correlation between choice reaction time and Inhibition (r = 1.005, 95 % CI [0.965, 1.045], p < .001) was not in the admissible range. These parameters suggest that despite the superior model fit, the four-factor solution was not admissible. In the three-factor model, there was also a strong correlation between inhibition+switching and choice reaction time (r = 0.992, 95 % CI [0.973, 1.010], p < .001), but updating were weakly correlated with choice reaction time (r = −0.228, 95 % CI [−0.406, −0.051], p < .05) and inhibition+switching (r = −0.211, 95 % CI [−0.391, −0.031], p < .05).

These findings indicate that inhibition, switching and choice reaction time are inseparable abilities, while updating is separable from these three. This is supported by the finding that indicators for updating loaded weakly or non-significantly in the one- and two-factor models and model fit were only acceptable in models in which there were separate factors specified for updating. Therefore, we constructed an alternative two-factor model with separate factors for inhibition+switching+choice reaction time and updating. In this model, the fit indices showed a good model fit: χ^2 (62) = 116.814, p < .001, RMSEA = 0.070, 90 % CI [0.050, 0.089], SRMR = 0.060, CFI = 0.963, TLI = 0.954. All indicators had significant loadings (0.371–0.943, 95 % CI [0.199, 0.967]), and there was a weak correlation between inhibition+switching+choice reaction time- and updating-factors (r = −0.222, 95 % CI [−0.398, −0.046], p < .05; Fig. 3).

To test whether our finding was not due to different metrics being used to measure these abilities (response time for inhibition, switching and choice reaction time, and accuracy scores for updating), the alternative two-factor model was reanalyzed using accuracy scores as the measures for all indicators. This model also showed a good fit: χ^2 (62) = 79.492, p = .0665, RMSEA = 0.039, 90 % CI [0.000, 0.063], SRMR = 0.060, CFI = 0.964, TLI = 0.955. All indicators had acceptable and statistically significant loadings for the EF-factor and there was no statistically significant correlation between the factors (Fig. 3). As some of the variables were slightly skewed (skewness value >1), the data was reanalyzed with transformed variables (reflect and Lg10), and the main findings remained the same.

4.3. The dimensionality of executive functions and choice reaction time at time point two

At time point two, the findings were similar to time point one. Fit for the four-factor model was significantly better than the three-factor model (see Appendix A), but as in time point one, choice reaction time, inhibition and switching had a very high correlation (r = 0.994, 95 % CI [0.968, 1.020] and 0.952, 95 % CI [0.912, 0.991]) respectively; (Appendix C), and inhibition+switching and choice reaction time was strongly correlated (r = 0.983, 95 % CI [0.965, 1.001]) in the three-factor model. As in time point one, a two-factor model with combined factors for choice reaction time, inhibition and switching, and a separate factor for updating were constructed. This model fitted the data well (χ^2 (62) = 122.852, p < .001, RMSEA = 0.073, 90 % CI [0.054, 0.092], SRMR = 0.042, CFI = 0.962, TLI = 0.952). In contrast to the time point one, there was no significant correlation between choice reaction time and updating. When the model was reanalyzed using accuracy scores as measures for all indicators, the model fit was good (χ^2 (62) = 70.091, p = .2247, RMSEA = 0.027, 90 % CI [0.000, 0.054], SRMR = 0.060, CFI = 0.984, TLI = 0.980). There was a weak positive correlation between the two factors (see appendix B).[1] As in time point one, the data was also reanalyzed with transformed variables (reflect and Lg10), and the main findings remained the same.

As the best-fitting model was similar at time point one and two, measurement invariance testing was conducted to examine the stability of the alternative two-factor model over time. First, a configural model that included both time points was constructed as the baseline model. In the second step, the factor loadings were constrained to be equal across two time points. In the third step, all intercepts were constrained to be equal over time. All three models tested showed an acceptable model fit to the data. There were no significant differences between the models

[1] As children without data from T1 were excluded from T2 analyses, findings were confirmed by testing all models with a full T2 sample (N = 273; Appendix E). The results remained the same. The alternative two-factor model fitted best to the data also with full T2 sample ((χ^2 (62) = 147.923, p < .001, RMSEA = 0.071, 90 % CI [0.057, 0.086], SRMR = 0.040, CFI = 0.965, TLI = 0.956)) and worked also with accuracy scores ((χ2 (62) = 74.148, p = .14, RMSEA = 0.027, 90 % CI [0.000, 0.047], SRMR = 0.056, CFI = 0.989, TLI = 0.986)).

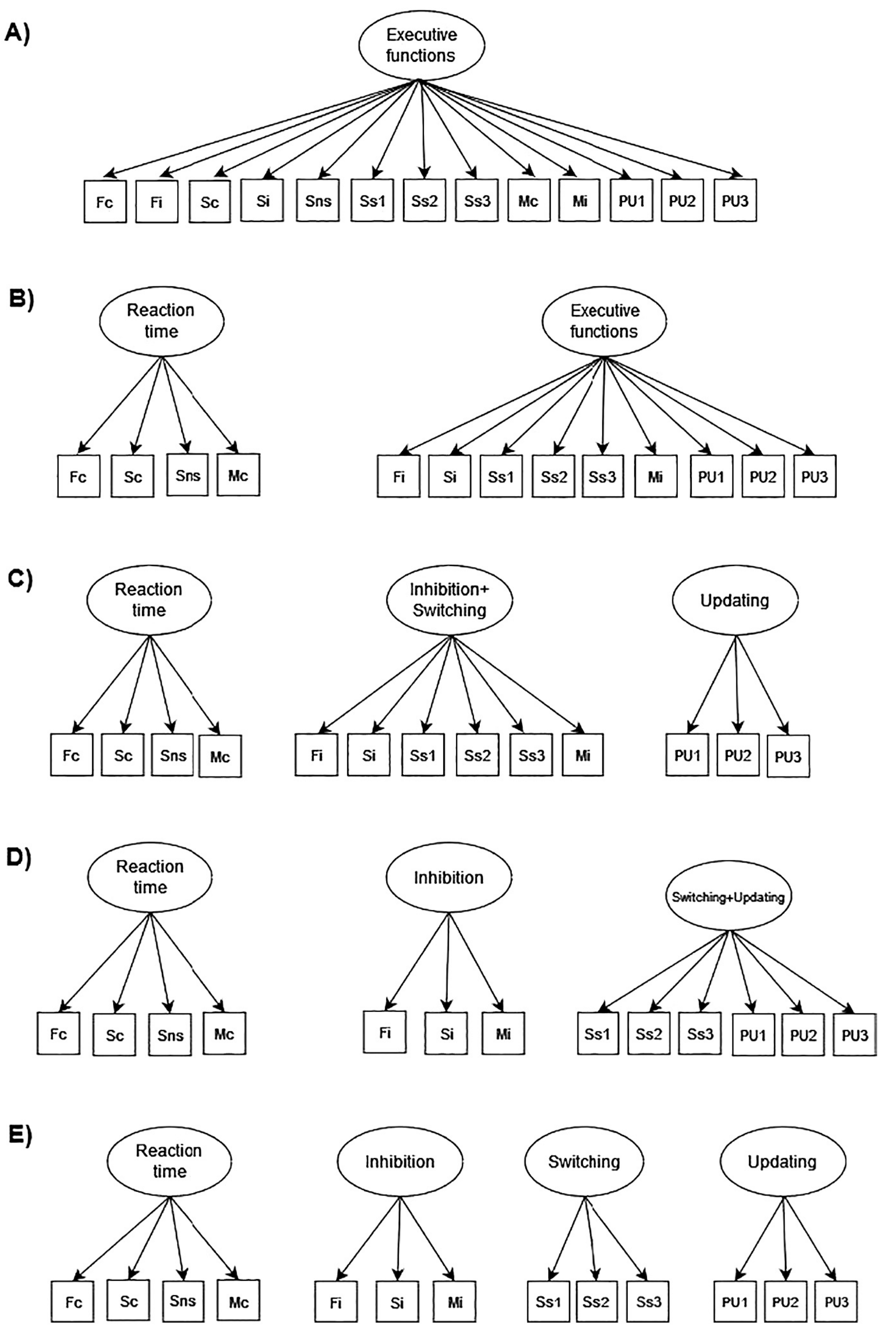

Fig. 1. CFA models tested.
Note. Fc = The Flanker congruent tasks, Fi = The Flanker incongruent tasks, Sc = The Simon congruent tasks, Si = The Simon incongruent tasks, Sns = The Simon no-switch tasks, Ss1 = The Simon switch tasks parcel 1, Ss2 = The Simon switch tasks parcel 2, Ss3 The Simon switch tasks parcel 3, Mc = The Mickey congruent tasks, Mi = The Mickey incongruent task, PU1 = The pictorial updating task parcel 1, PU2 = The pictorial updating task parcel 2, PU3 = The pictorial updating task parcel 3.

Table 4
Fit indices for the CFA-models and chi-square difference test in time point one.

Model	χ^2			RMSEA		AIC	SRMR	CFI	TLI
	Value	df	p	Value	90 % CI				
1-factor	250.59	63	0.0000	0.128	[0.112, 0.145]	4516.5	0.100	0.874	0.844
2-factors: RT & EF	349.85	62	0.0000	0.129	[0.113, 0.146]	4517.8	0.100	0.873	0.841
3-factors: RT, Inh/Sw, U	115.69	60	0.0000	0.071	[0.052, 0.091]	4387.6	0.06	0.962	0.951
3-factors: RT, Inh, Sw/U	235.50	60	0.0000	0.127	[0.110, 0.144]	4507	0.099	0.882	0.846
4-factors: RT, Inh, Sw, U	98.81	57	0.0005	0.063	[0.042, 0.084]	4376.7	0.056	0.972	0.961
Model comparison					$\Delta\chi^2$	Δdf		p	
3-factors: RT, Inh/Sw, U vs. 4-factors: RT, Inh, Sw, U					16.88	3		<0.001	

Note. RT = Reaction time, EF = Executive functions, Inh = Inhibition, Sw = Switching, U = Updating.

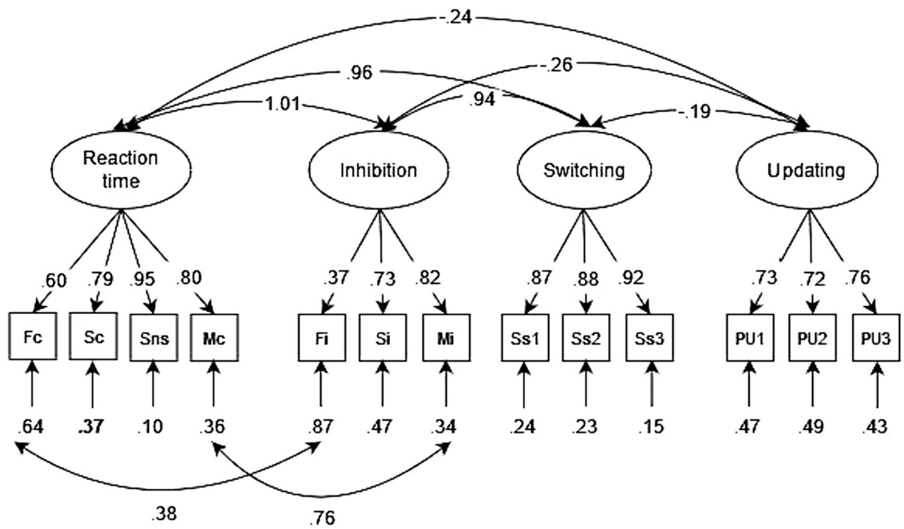

Fig. 2. Standardized solution for the four-factor model with latent factors of reaction time, inhibition, switching and updating in time point one.

Note. Fc = The Flanker congruent tasks, Fi = The Flanker incongruent tasks, Sc = The Simon congruent tasks, Si = The Simon incongruent tasks, Sns = The Simon no-switch tasks, Ss1 = The Simon switch tasks parcel 1, Ss2 = The Simon switch tasks parcel 2, Ss3 The Simon switch tasks parcel 3, Mc = The Mickey congruent tasks, Mi = The Mickey incongruent task, PU1 = The pictorial updating task parcel 1, PU2 = The pictorial updating task parcel 2, PU3 = The pictorial updating task parcel 3.

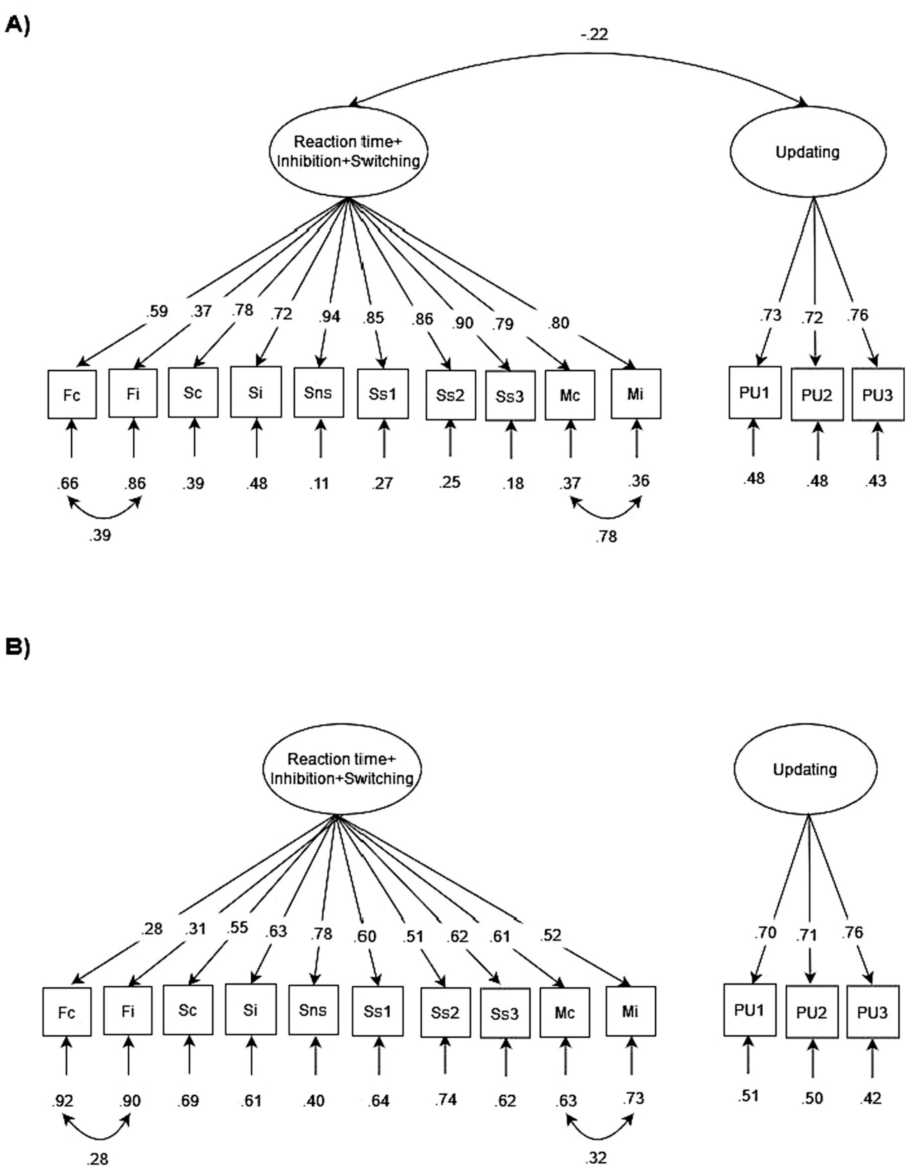

Fig. 3. Standardized solution for the two-factor model with latent factors of Reaction time/inhibition/switching and updating in time point one. Measures used for reaction time, inhibition and switching: A) Response time, B) Correct responses.

Note. Fc = The Flanker congruent tasks, Fi = The Flanker incongruent tasks, Sc = The Simon congruent tasks, Si = The Simon incongruent tasks, Sns = The Simon no-switch tasks, Ss1 = The Simon switch tasks parcel 1, Ss2 = The Simon switch tasks parcel 2, Ss3 The Simon switch tasks parcel 3, Mc = The Mickey congruent tasks, Mi = The Mickey incongruent task, PU1 = The pictorial updating task parcel 1, PU2 = The pictorial updating task parcel 2, PU3 = The pictorial updating task parcel 3.

Table 5
Model fit indices for longitudinal measurement invariance testing for alternative 2-factor model.

Model	Constraints	χ^2	df	p	$\Delta\chi^2$	Δdf	p ($\Delta\chi^2$)	RMSEA	SRMR	CFI	TLI
1	Configural: no constraints	458.353	276	<0.001				0.060	0.064	0.944	0.934
2	Factor loadings	472.561	287	<0.001	14.208	11	0.2217	0.060	0.069	0.943	0.935
3	Intercepts	473.419	300	<0.001	15.066	24	0.9188	0.056	0.069	0.947	0.942

(Table 5) indicating that there are no differences in the factor structure between time point one and two (Chen, 2007).

5. Discussion

In this study, we investigated the dimensionality of EF and processing speed in 3–6 years old preschoolers by using confirmatory factor analysis on data from two measurement points. First, in line with our first hypothesis, we found that it was possible to distinguish two EF dimensions: one for inhibition and switching, and one for updating. Second, processing speed was found to be separable from updating, but not from inhibition and switching, lending partial support for our second hypothesis. Thus, the best fitting model showed separate dimensions for (1) inhibition, switching and processing speed, and (2) updating. The findings were similar at both time points.

Our finding that inhibitions and switching are inseparable from processing speed is line with previous studies reporting strong association between EF and processing speed in preschoolers (Clark et al., 2014; Lee et al., 2013 ; van der Ven et al., 2013 ; Willoughby et al., 2020) and school-aged children (McAuley & White, 2011; Rose et al., 2011; Span et al., 2004). Similar to our findings, Clark et al. (2014) reported that in three years old children, processing speed explained all of the variance in children's performance in EF tasks. These findings together with our findings suggest that EF and processing speed are strongly co-dependent in this age group and that variation in EF, especially in inhibition and switching, is primarily explained by differences in processing speed (Clark et al., 2014). It has been argued that children with faster information processing speed have better EF performance as processing speed enables children to maintain and manipulate more information in mind (McAuley & White, 2011). The association between EF and processing speed has been also explained through other cognitive abilities, as there is evidence that processing speed mediates the development in other cognitive abilities (Christ et al., 2003; Fry & Hale, 1996; Kail, 2007). Our study adds to the previous evidence that while inhibition, switching and processing speed are inseparable, updating and processing speed are independent from each other in preschoolers. This is in line with previous studies reporting that processing speed is stronger associated with inhibition and switching than updating in preschoolers (Lee et al., 2013; van der Ven et al., 2013; Willoughby et al., 2020).

Contrary to our findings, Clark et al. (2014) found that processing speed and EF were distinguishable in 4.5- and 5-years old children. As the authors concluded, different metrics used to measure EF (accuracy scores) and processing speed (response time) might explain the distinction between EF and processing speed found in their study. In our present study, inhibition, switching and processing speed were found to be inseparable in both time points, when response time was used as a measure for both components as well as using accuracy scores for both components.

Based on previous studies and our findings, processing speed seems to be strongly associated with EF in preschoolers, and therefore it is reasonable to consider processing speed as a control measure, when examining the structure of EF. Two distinguishable dimensions for EF have been found (Lee et al., 2013; Monette et al., 2015; van der Ven et al., 2013) in studies that have adjusted processing speed when examining the dimensionality of EF. In line with our findings, updating was found to be a separate dimension from inhibition and switching in approximately 6 years old children (Lee et al., 2013; van der Ven et al., 2013). In the previous studies, inhibition and switching have been shown to be inseparable in school-aged children (Nelson et al., 2022) and there is evidence that differentiation can not be clearly seen until 11 years (Lee et al., 2013). Inseparability of inhibition and switching components might be explained by similarities in measures as both types of tasks include the requirement of the resolution of the conflicting stimulus in both inhibition and switching tasks (Garon et al., 2008; van der Ven et al., 2013). However, separate inhibition- and updating+switching-dimensions have been also found (Monette et al., 2015). According to Monette et al. (2015), tasks used to measure updating included demands of switching that might explain their findings. Many of the previous EF studies that have not controlled for processing speed have found an unidimensional structure for EF (e.g., Hughes et al., 2009; Shing et al., 2010; Wiebe et al., 2008; Willoughby et al., 2012) and it might be that processing speed as a common source of variation in EF-tasks have masked the difference between the EF-dimensions.

It is possible that methodological choices at least partly explain this strong association between inhibition, switching and processing speed in the present study. It has been argued that, if tasks used to measure EF are too similar, there are still non-executive aspects present in the latent factor (Miyake et al., 2000). We used different conditions from the same tasks to construct inhibition, switching and choice reaction time factors, which may have masked differences between inhibition, switching and choice reaction time as there might be some task specific non-executive abilities captured by latent variables. Although we used conditions from two or more different tests to construct factors for different components of EF, there were visual stimuli and the response was performed by pressing with a finger in all tasks. In addition, in all three tasks (The Flanker, Simon, and Mickey) the characteristics of visual stimuli and required response (pressing one of two keys) is the same in all trials requiring activity of posterior attentional network (Corbetta & Shulman, 2002). This leads to top-down control of attention, as this cognitive information is used to direct attention to a relevant object (Corbetta & Shulman, 2002). To obtain a more holistic measure of children's ability to respond to visual stimuli in future studies, it would be beneficial to include trials with some unexpected stimuli to activate other attentional networks. These similarities in task characteristics may make it more difficult to distinguish inhibition, switching and processing speed as latent factors might have captured non-executive characteristics specific to this type of tasks (van der Sluis et al., 2007). Trials preceded by a change between congruent and incongruent trials (or vice versa) were used as indicators for switching. The switching component in these trials is not as strong as in many of previous studies using switching tasks including clear change in the rules or task alternation (Rose et al., 2011), hence switching and inhibition factors may not have been so easily distinguished in our study.

The tasks measuring inhibition, switching and processing speed seem to be quite easy for children as the accuracy scores were generally very high, which might explain the finding that inhibition, switching and processing speed represent the same dimension. If the task does not sufficiently challenge the EF, it may fail to capture various EF abilities and therefore the processing speed becomes a more important variable to explain the performance. However, in all conditions used in the CFA, responses were faster in conditions not requiring switch or inhibition than in corresponding EF conditions suggesting that EF conditions were significantly more difficult. It has been also suggested that, especially in young children, high levels of within-person variability in non-cognitive variables (e.g., motivation) can influence task performance, and might mask the real difference between EF and processing speed (Clark et al., 2014). There are also some limitations in using response time as a measure of EF and processing speed in early childhood. Children may prioritize accuracy over speed of response, or vice versa (Heitz, 2014), which might be influenced by individual cognitive style (impulsivity versus reflectivity). In the present study, accuracy and response time correlated significantly only in one of the conditions (Flanker incongruent in time point two) used in CFA models, indicating that speed-accuracy trade-offs do not affect results much. In addition, findings were confirmed by reanalyzing the main model using accuracy scores as a measure for all indicators.

The reliability was lower in congruent trials in the Flanker task at time point one. The Flanker congruent task was the first EF task for children, and therefore unfamiliarity with the task might explain unstable performance in these trials. In the Mickey and Simon tasks, reliability was lower at time point two compared to time point one. It might be that older children shift their focus from accuracy to faster response, as they have already mastered the foundational skills to complete the task. This might lead to more errors in accuracy compared with performance at younger ages. However, decreases in reliability were only seen in the Simon and Mickey tasks, but not in the Flanker task. This may be explained by the difficulty of Mickey and Simon compared to Flanker.

One limitation in the present study was that we had only one task for updating and therefore we used parcels as indicators for the Updating factor. In addition, in time point one, the Simon switch task was the only indicator for the Switching factor. This might have led to task-common non-executive abilities to be present in these factors (Little et al., 2002) Constructing latent factor by using more tasks would have offered a purer measure for updating, and switching performance in time point one. However, due to the young age of the children, we were able to use only four different tasks to keep the total test time feasible. Another limitation of the present study was that children with a relatively wide age range were studied together. EF performance improves rapidly during the preschool years (e.g., Zelazo et al., 2003) and there might be significant variation within individuals in the development. Howard et al. (2015) used a narrow age range for 3 and 4-year olds and found that different EF-dimensions (inhibition, switching, updating) were stronger associated among 4-year olds than 3-year olds challenging the idea of a single developmental trajectory that various dimensions of EF become increasingly separate with age. Unfortunately, due to the disruption imposed by COVID-19 pandemic, we were unable to use narrower age groups in our study. Future studies should focus on studying the structure of EF in preschools using CFA with a narrower age range to better understand the developmental trajectories in the structure of EF and processing speed. In addition, only one type of reaction time task (choice reaction time) was used to measure processing speed. In the choice reaction time tasks, the characteristics of stimuli changes, while in simple reaction tasks there is only one possible stimuli. Using both types of reaction time tasks would have offered a more holistic measure of processing speed. The practice effect is one important challenge that should be considered when the measurements are repeated with children. In this study, we do not think there was a significant practice effect influencing the results, as there was no feedback given for children during tasks, the time between measurements was quite long, and the performance between time points was not compared with each other.

Despite these limitations, we used an appropriate statistical approach (CFA) with validate measures of processing speed, response inhibition, and updating to examine the dimensionality of EF and processing speed in preschoolers with two measurement points. We found two dimensions: one for inhibition, switching and processing speed, and one for updating exist in 3–6 years old preschoolers. These findings indicate that processing speed explains a high proportion of the variation in inhibition and switching performance, but not the performance in updating in young children.

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CRediT authorship contribution statement

Anssi Vanhala: Conceptualization, Methodology, Data collecting, Formal analysis, Writing - Original Draft.
Kerry Lee: Conceptualization, Formal analysis, Methodology, Paper editing.
Johan Korhonen: Conceptualization, Formal analysis, Methodology, Paper editing.
Pirjo Aunio: Conceptualization, Methodology, Supervision, Resources, Funding acquisition, Paper editing.

Declaration of competing interest

None.

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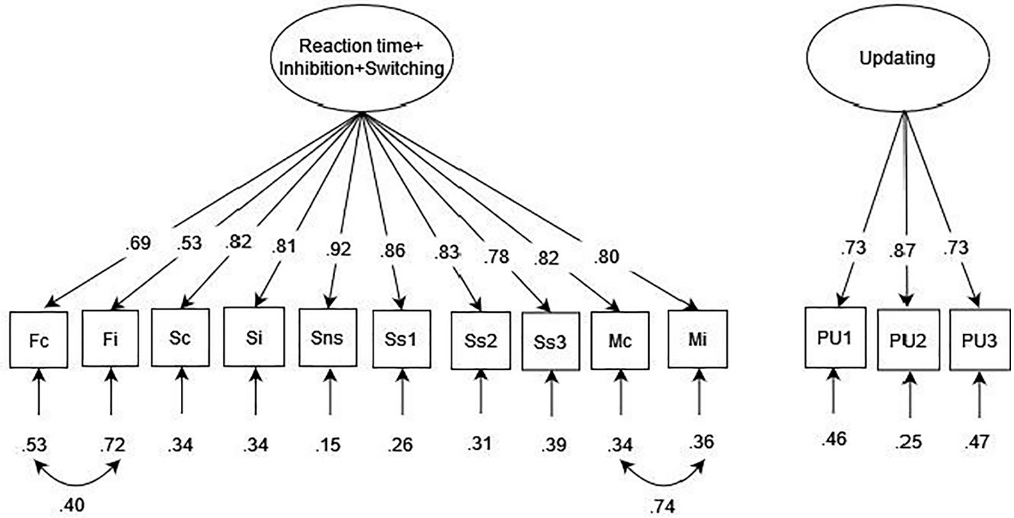
Appendix A. Fit indices for the CFA-models and chi-square difference test in time point two

Model	χ^2			RMSEA		AIC	SRMR	CFI	TLI
	Value	df	p	Value	90 % CI				
1-factor	311.11	63	0.0000	0.147	[0.131, 0.164]	4955.8	0.109	0.846	0.809
2-factors: RT & EF	Not identified	–	–	–	–	–	–	–	–
3-factors: RT, Inh/Sw, U	118.61	60	0.0000	0.073	[0.054, 0.093]	4769.3	0.042	0.964	0.953
3-factors: RT, Inh, Sw/U	301.87	60	0.0000	0.149	[0.132, 0.166]	4952.6	0.108	0.850	0.805
4-factors: RT, Inh, Sw, U	109.61	57	0.0000	0.071	[0.051, 0.091]	4766.3	0.036	0.967	0.955
Model comparison					$\Delta\chi^2$	Δdf		p	
3-factors: RT, Inh/Sw, U, vs. 4-factors: RT, Inh, Sw, U					9	3		0.029	

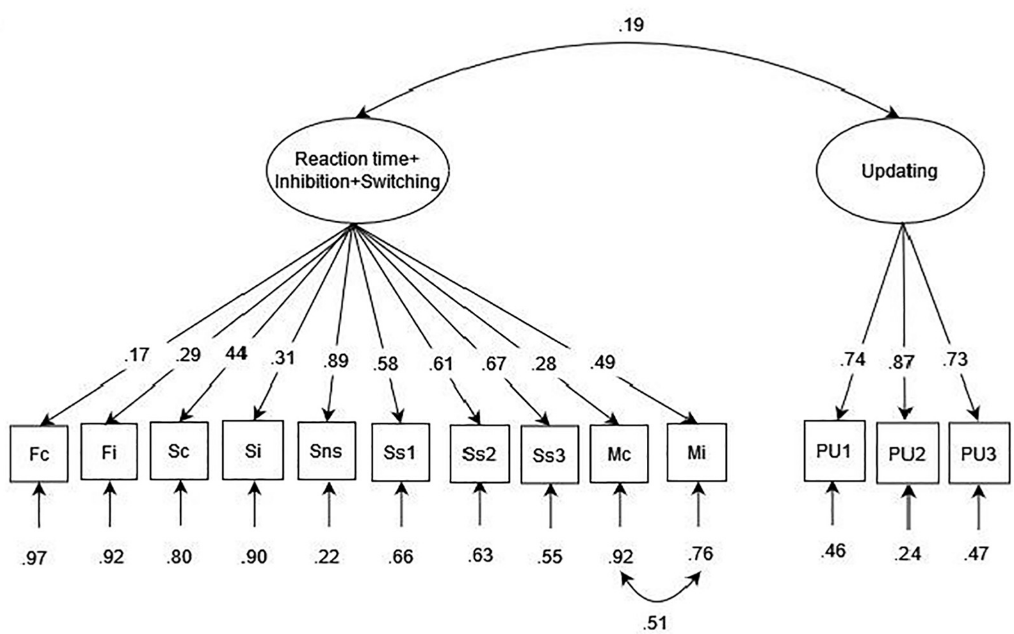
Note. RT = Reaction time, EF = Executive functions, Inh = Inhibition, Sw = Switching, U = Updating.

Appendix B. Standardized solution for the two-factor model with latent factors of Reaction time/inhibition/switching and updating in time point two. Measures used for reaction time, inhibition and switching: A) Response time, B) Correct responses

A)

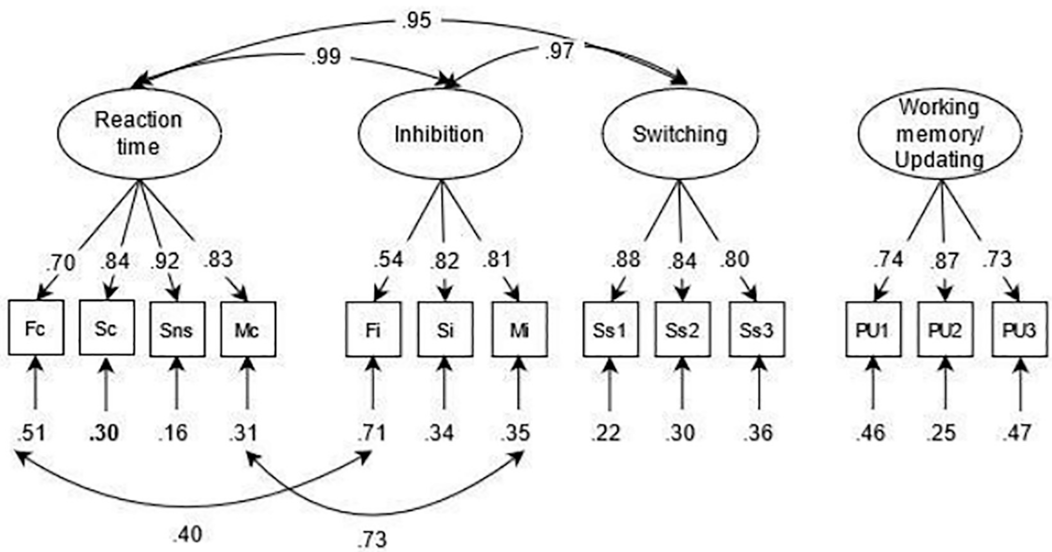


B)



Note. Fc = The Flanker congruent tasks, Fi = The Flanker incongruent tasks, Sc = The Simon congruent tasks, Si = The Simon incongruent tasks, Sns = The Simon no-switch tasks, Ss1 = The Simon switch tasks parcel 1, Ss2 = The Simon switch tasks parcel 2, Ss3 The Simon switch tasks parcel 3, Mc = The Mickey congruent tasks, Mi = The Mickey incongruent task, PU1 = The pictorial updating task parcel 1, PU2 = The pictorial updating task parcel 2, PU3 = The pictorial updating task parcel 3.

Appendix C. Standardized solution for the four-factor model with latent factors of Reaction time, Inhibition, Switching and Working Updating in time point two



Note. Fc = The Flanker congruent tasks, Fi = The Flanker incongruent tasks, Sc = The Simon congruent tasks, Si = The Simon incongruent tasks, Sns = The Simon no-switch tasks, Ss1 = The Simon switch tasks parcel 1, Ss2 = The Simon switch tasks parcel 2, Ss3 The Simon switch tasks parcel 3, Mc = The Mickey congruent tasks, Mi = The Mickey incongruent task, PU1 = The pictorial updating task parcel 1, PU2 = The pictorial updating task parcel 2, PU3 = The pictorial updating task parcel 3.

Appendix D

D.1. Unstandardized solution for the alternative two-factor model in time point one

Observed variable	Factor loading				Residual vVariance			
	Response time	p	Accuracy	p	Response time	p	Accuracy	p
The Flanker Congruent	1.000	999.000	1.000	999.000	0.648	0.000	0.917	0.000
The Flanker Incongruent	0.647	0.000	1.117	0.020	0.884	0.000	0.906	0.000
The Simon Congruent	1.333	0.000	1.997	0.005	0.383	0.000	0.691	0.000
The Simon Incongruent	1.233	0.000	2.253	0.004	0.471	0.000	0.610	0.000
The Simon No-Switch	1.608	0.000	2.804	0.004	0.109	0.000	0.402	0.000
The Simon Switch, parcel 1	1.456	0.000	2.142	0.004	0.267	0.000	0.638	0.000
The Simon Switch, parcel 2	1.474	0.000	1.820	0.006	0.249	0.000	0.735	0.000
The Simon Switch, parcel 3	1.543	0.000	2.219	0.005	0.179	0.000	0.612	0.000
The Mickey Congruent	1.364	0.000	2.193	0.004	0.368	0.000	0.633	0.000
The Mickey Incongruent	1.375	0.000	1.867	0.006	0.359	0.000	0.730	0.000
The Pictorial Updating, Parcel 1	1.000	999.000	1.000	999.000	0.470	0.000	0.494	0.000
The Pictorial Uupdating, Parcel 2	0.992	0.000	1.038	0.000	0.478	0.000	0.455	0.000
The Pictorial Updating, Parcel 3	1.042	0.000	1.068	0.000	0.425	0.000	0.423	0.000

D.2. Unstandardized solution for the alternative two-factor model in time point two

Observed variable	Factor loading				Residual variance			
	Response time	p	Accuracy	p	Response time	p	Accuracy	p
The Flanker Congruent	1.000	999.000	1.000	999.000	0.551	0.000	0.961	0.000
The Flanker Incongruent	0.773	0.000	1.698	0.076	0.731	0.000	0.909	0.000
The Simon Congruent	1.177	0.000	2.601	0.057	0.339	0.000	0.807	0.000
The Simon Incongruent	1.233	0.000	1.821	0.079	0.343	0.000	0.899	0.000
The Simon No-Switch	1.174	0.000	5.327	0.049	0.153	0.000	0.228	0.000
The Simon Switch, parcel 1	1.247	0.000	3.384	0.049	0.261	0.000	0.656	0.000
The Simon Switch, parcel 2	1.199	0.000	3.904	0.050	0.315	0.000	0.624	0.000
The Simon Switch, parcel 3	1.126	0.000	3.904	0.050	0.394	0.000	0.546	0.000
The Mickey Congruent	1.191	0.000	1.668	0.091	0.348	0.000	0.928	0.000
The Mickey Incongruent	1.167	0.000	2.930	0.058	0.373	0.000	0.804	0.000
The Pictorial Updating, Parcel 1	1.000	999.000	1.000	999.000	0.455	0.000	0.455	0.000
The Pictorial updating, Parcel 2	1.183	0.000	1.183	0.000	0.243	0.000	0.242	0.000

Appendix E. Indices for the CFA-models and chi-square difference test in time point two with full sample (N = 273)

Model	χ^2			RMSEA		AIC	SRMR	CFI	TLI
	Value	df	p	Value	90 % CI				
1-factor	422.84	63	0.0000	0.145	[0.132, 0.158]	6984.7	0.107	0.852	0.817
2-factors: RT & EF	419.72	62	0.0000	0.145	[0.132, 0.159]	6983.6	0.107	0.853	0.815
3-factors: RT, Inh/Sw, U	143.95	60	0.0000	0.072	[0.057, 0.087]	6711.8	0.040	0.965	0.955
3-factors: RT, Inh, Sw/U	403.90	60	0.0000	0.145	[0.132, 0.158]	6971.8	0.105	0.859	0.816
4-factors: RT, Inh, Sw, U	127.37	57	0.0000	0.067	[0.052, 0.083]	6701.3	0.036	0.971	0.960
Model comparison					$\Delta\chi^2$	Δdf		p	
3-factors: RT, Inh/Sw, U, vs. 4-factors: RT, Inh, Sw, U					16.58	3		<0.001	

Note. RT = Reaction time, EF = Executive functions, Inh = Inhibition, Sw = Switching, U = Updating.

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