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A one-year follow-up of the cognitive and psycho-behavioural skills in artistic gymnastics

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Declaration of interest

None

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Author contributions

FL, DC and ML were involved in the conceptualization of the study. FL was involved in data collection. FL, FD, DC, PV, and ML were involved in data analysis and in the writing of the manuscript. All authors contributed to and approved the final version of the manuscript.

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Psychology of Sport and Exercise

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Abstract

A good set of cognitive and psycho-behavioural skills are beneficial for young athletes to overcome and benefit from developmental challenges. Unfortunately, there is still a dearth of knowledge on how both these cognitive (i.e., executive functions; EF) and psycho-behavioural (i.e., psychological characteristics of developing excellence; PCDE) skills develop in youth athletes. Especially for athletes in early specialisation sports such as artistic gymnastics, the early EF and PCDE development might be important to be able to cope with the pressure and challenges that comes with a transition to the next stage. In the current study, artistic gymnasts between 9 and 22 years old were tested twice with a 12-month interval to investigate the changes in EF and PCDE. Results showed that EF developed within the youngest stage, but plateaued at the later stages. Most PCDE did not seem to change over time within each stage. Furthermore, the transition to a new stage does not seem to coincide with an increased improvement of PCDE. However, with a case study approach in the oldest stages, still inter-individual differences in EF and PCDE scores over time were observed. This study shows that EF and PCDE develop over time, albeit in a non-linear way, and along a variety of developmental trajectories.

Keywords

Talent development, executive functions, psychological characteristics, adolescents, artistic gymnasts

Introduction

Young athletes encounter many challenges along their road to expert performance. They face opportunities (e.g., selection for a big competition), set-backs (e.g., injuries), and transitions (e.g., transfer to the better team) along the pathway of realising their potential and becoming a high-performing athlete. Some of these challenges come naturally in the talent development pathway, such as the transitions between the 'macro stages' of talent development (e.g., transitioning from aspiring to junior; or junior to senior athlete). Importantly, however, athletes also have to act upon many unexpected positive and negative challenges during their way to success, such as an unexpected selection for a competition, injuries or technique changes (Ollis et al., 2006). In the first year of transitioning stages especially, athletes seem to struggle with these challenges, often with a negative impact on their performance (Gallo et al., 2022; Knight et al., 2018).

To help athletes cope, overcome and even benefit from developmental challenges, it is key to develop good cognitive and psycho-behavioural skills (Gould et al., 2002; MacNamara et al., 2010b; MacNamara & Collins, 2013). When focusing on the cognitive skills, executive functions (EF) could play an important role during the talent development process. EF are the higher-order control processes involved in goal-directed behaviour (Baggetta & Alexander, 2016) regulating cognitive, emotional and motor activities, and enabling purposeful and goal-directed behaviour, especially when learning or facing a novel task or complex situation (Theodoraki et al., 2019). Shifting, working memory and inhibition are generally accepted as the three domain-general EF (Diamond, 2013; Miyake et al., 2000). Shifting is defined as the ability to shift back and forth between tasks, operations and/or mental sets (Monsell, 1996). Working memory requires the updating and monitoring of incoming information of relevance for the task at hand (Miyake et al., 2000). The third component, inhibition, concerns the ability to deliberately inhibit dominant, automatic or prepotent responses when necessary (Miyake et al., 2000). Other studies would categorize the cognitive processes rather in one (Prencipe et al., 2011), two (Huizinga et al., 2006) or even four components (i.e. adding verbal fluency; (Fournier-Vicente et al., 2008; Gustavson et al., 2019; Sinzig et al., 2008). Laureys and colleagues (2022) for example, also found planning to be a core EF component, next to the three components suggested by Miyake et al. (2000). Planning is then defined as the ability to map out a sequence of actions in preparation for a particular task (Morris et al., 1997).

In the sport context, some studies have reported that athletes perform better on these EF compared to non-athletes (Voss et al., 2010) and even that highly skilled athletes outperform lower skilled ones (Scharfen & Memmert, 2019; Verburgh et al., 2014; Vestberg et al., 2017). However, other studies could not replicate these results and found no discrepancies in domain-general EF performance and expertise level (Kida et al., 2005; Lundgren et al., 2016; Nakamoto & Mori, 2008), leading to a lack of agreement of the importance of EF in sport performance. Furthermore, most research on EF development has only included samples of the general population, and longitudinal studies mapping EF development in an athletic population are missing (Beavan et al., 2020). In the general population, there is a rapid improvement of EF performance during childhood, which then levels off during early adolescence and reaches adult level at young adulthood (Anderson et al., 2001; Best & Miller, 2010; Huizinga et al., 2006). Following the broad-skill hypothesis, it could be suggested that young athletes could improve their domain-general EF performance by prolonged learning experiences in other, related skills (Furley & Memmert, 2011) or by dealing with more cognitive demands during their talent development pathway than their age-related peers (Furley & Memmert, 2011; Jacobson & Matthaeus, 2014; Taatgen, 2013). This could indicate that the EF developmental trajectories of athletes increase even more when deliberate practice starts compared to the general population, and EF performance could potentially increase after adolescence as well. Along with the observation that athletes continuously need to learn new techniques or have to make behavioural decisions when defying new environmental situations, it is important to identify and map the development of (domain-general) EF purposeful features for young, talented athletes.

Research has found associations between cognitive functions and psycho-behavioural skills. As one pertinent example, numerous studies have shown that EF could underpin self-regulation (Hyland-Monks et al., 2018), which enables athletes to control their thoughts, feelings and actions (Vohs & Baumeister, 2004) and is seen as a key psycho-behavioural determinant for elite athletes (Toering et al., 2009). Next to self-regulation, athletes can benefit from higher levels and continuous improvement of a range of psycho-behavioural skills. Compared to the rather robust cognitive processes underlying EF, psycho-behavioural skills are specific thoughts and behaviours that can help regulate an athlete's state of mind during practice and performance (e.g., goal setting, coping skills). These skills are mediated by environmental change, such as contextual and psychosocially factors (Dohme et al., 2017; Henriksen et al., 2010; Larsen et al., 2012) or performance challenges (Hyland-Monks et al., 2018; MacNamara et al., 2010; Toering et al., 2009; Vohs & Baumeister, 2004). Earlier research succeeded in distinguishing high-performing athletes from their less successful peers (Durand-Bush & Salmela, 2002; Gould et al., 1999), based on outstanding performances on for example self-determination, focus, or mental preparation. Moreover, some studies also suggest that younger athletes will benefit from a good set of psycho-behavioural skills to successfully face and overcome environmental inputs or challenges during their talent development pathway (Abbott & Collins, 2004; Gould et al., 2002; Knight et al., 2018; MacNamara et al., 2010; MacNamara & Collins, 2013; Taylor & Collins, 2021).

One specific set of psycho-behavioural skills important for young, talented athletes are the psychological characteristics of developing excellence (PCDE), a set of skills and associated behaviour athletes need or will benefit from during their talent development (MacNamara et al., 2010a, 2010b). The majority of the PCDE are adaptive skills and characteristics (e.g. use of imagery or self-directed control), but there are also psychological characteristics identified that have a maladaptive (e.g. eating disorders or anxiety-related behaviours) or even a dual-effect (e.g. perfectionism) on the talent development pathway. Several studies examined the PCDEs in specific sport contexts, and did find a specific set of skills needed in a specific sport (Barquin et al., 2019). A discrimination could also be made between the good (high-performing) and poor performers (MacNamara & Collins, 2013), dependent on the type of sport. Good developers in team sports for example, used more coping skills and were better at evaluating their performance, while good developers in individual sports scored higher on imagery skills and skills related to organisation and engagement in quality practice Depending on the type of sport, the needs and requirements in talent development stages alter, so that psycho-behavioural skills will be required to positively cope with the demands. Correct deployment of the PCDE skill-set will help the youth athlete both during practice and competition situations (MacNamara & Collins, 2013). Nevertheless, although one study found an improvement of the PCDEs over time (Saward et al., 2020), only a limited amount of studies investigated the development of PCDEs over more than one year. Therefore there is an urgent need for more longitudinal studies mapping the development of the PCDEs in specific sport settings.

When athletes transition to the next developmental stage, this coincides with more challenges in both the athletic and non-athletic domain (Morris, 2013). Athletes start in aspiring stages, only competing at national level, and aim to eventually compete at the Olympic Games (or other high-stake international competitions) during their senior stage. In sport transition literature, most research efforts are made on the junior-to-senior transition as this is often described as the most difficult talent development transition in athletes' careers (Drew et al., 2019; Stambulova et al., 2009). In early specialisation sports, such as artistic gymnastics, these tough developmental transitions could occur sooner (e.g., transitioning to junior level) given that these sports already have high physical (e.g., high amounts of training hours) and mental (e.g., learning difficult and scary technical skills or competing internationally) demands at (pre-)puberty ages. Given the challenges put on these athletes at already young ages, attrition rates before reaching the senior stage are fairly high (Pion et al., 2015). To avoid high drop-out rates at the younger ages and during earlier transitions, whilst also offering protection against negative experiences, one approach could be to focus more on EF and PCDE. With a stronger cognitive and psycho-behavioural skill-set, athletes could be able to face and overcome challenges, rather than letting the challenge overcome them. It is thus important to examine the general developmental profiles at younger ages and earlier transition stages (aspiring-to-junior) in early specialisation sports such as artistic gymnastics.

Early specialisation athletes transition stages at earlier ages than team sports and late-specialisation sports, consequently those athletes in early specialisation sports will need larger amounts of deliberate practice at younger ages. This, in turn, could influence the timing of facing new challenges, and thus the level of importance, development and deployment of EF and PCDE at younger ages (MacNamara & Collins, 2013). Next to the type of sport, there is also a constant change in requirements inherent to the talent development process. Technical and physical demands increase throughout developmental stages, together with an increase in environmental challenges (change of training venues, entering boarding school, other coaches, other life challenges, new teammates, etc.). In addition, cognitive, psychological, and emotional maturational processes are still continuing at these developmental ages (Drew et al., 2019). The rate of this maturation and growth processes differs between individuals (Knight et al., 2018). Consequently, it can be assumed that the EF and PCDE requirements also vary within and between individuals over time, depending on the developmental stage and experience (Abbott & Collins, 2004; MacNamara et al., 2010a, 2010b).

The dearth of knowledge in EF and PCDE development in young athletes within an early specialisation sport requires more attention. Cognitive and psych-behavioural skills could have an impact during talent development, especially for those athletes who transition stages and have to cope with changing and/or more-demanding requirements and challenges. Accordingly, in the first part of this study, EF and PCDE development over one year was investigated in artistic gymnasts aged 9 to 22 years old. Specifically, we examined both gymnasts who stayed in the same stage and gymnasts who transitioned from one stage to the next over the one-year time period. We hypothesized that (a) the EF developmental trajectory would mainly be similar to that of a general population (rapid increase during the aspiring and junior stage or late childhood and early adolescence), although we expect a longer increase of EF performance given the broad-skill hypothesis (slow increase during senior stage or late adolescence) than in the general population. Because of the rather robust character of EF, we did not expect a difference for gymnasts staying in the same stage or transitioning stages here, Since PCDE are more influenced by social and environmental factors compared to EF, (b) we expected an increase in score for gymnasts staying in the same stage (at the aspiring, junior and senior stage), although a post-transition discontinuation or even a decline might be expected in gymnasts that transition to a next stage in all talent developmental stages. In the second part of this study, a case study approach was used to qualitatively explore if variability in development in EF and PCDE scores is still apparent in individuals at the later stages. Although inter-individual variation within EF and within PCDE scores was expected, we examined if (c) a general trend could be observed when comparing the EF component and PCDE factor scores between individuals and between gymnasts staying in the same stage or transitioning stages.

Method

Participants. This study included participants who were part of a longitudinal project covering three years. Data were collected at test days organised at the Flemish Gymnastics

Federation between April 2018 and March 2021. The participants in this study were artistic gymnasts between 9 and 22 years old in the first year of testing (12.9 ± 2.87), and were actively competing at the highest level in their age group. Three age groups, or talent development stages, were used here: aspiring, junior or senior stage. The division into these talent stages was based upon international age stages, taking into account the minimum age of participating at the Olympic Games per sex. Characteristics of each talent stage are presented under Supplementary Material 1. From the original sample gathered over three years of 178 male and female gymnasts, 53 gymnasts completed the cognitive and psycho-behavioural measurements in two consecutive years and were retained for this study. Table 1 gives detailed information about the age, sex and stage of the gymnasts at baseline measurement.

Informed consent was obtained from each participant. Parents or legal representative for participants younger than 18 years old, gave their informed consent to let their child participate in this study. This study was conducted in accordance with the code of Ethics of the World Medical Association (Declaration of Helsinki, 1964, and Declaration of Tokyo, 1975, as revised in 1983) and was approved the local ethics committee of Ghent University Hospital.

*** Insert Table 1 ***

Instruments.

Cambridge Brain Sciences. A multidimensional web-based test battery from Cambridge Brain Sciences (CBS) was used. The tests used in the CBS are all computerised versions of well-known and widely used neuropsychological tests to measure EF constructs (for a detailed overview for each test and its reliability measure; see Supplementary Material 2). The test battery can contain up to thirteen EF tests, including a wide range of outcome variables. In this study, seven CBS-tasks with minimal academic influence (i.e., reading and mathematical skills) and examining all four EF components were chosen: Spatial Span, Double Trouble, Token Search, Odd One out, Spatial Planning, Monkey Ladder and Sustained Attention to Response tasks (SART). The Spatial Span (based on the Corsi Block Tapping Task; Corsi, 1972), Token Search (or Spatial Search Task, Collins et al., 1998) and Monkey Ladder (visual-spatial working memory task; Inoue & Matsuzawa, 2007) assess visual-spatial working memory. The Double Trouble (adapted Stroop task; Stroop, 1992) and the Sustained Attention to Response (Go/No-Go task; Robertson et al., 1997) are included to asses inhibition. The Odd One Out (fluid intelligence test, Brenkel et al., 2017) evaluates shifting performance and the Spatial Planning (Tower of Londen task; Shallice, 1982) for planning performance. Tests were always assessed in the same order stated above and online, using a 9.7-inch iPad 2017 (iOS 12.1, Apple Inc, Cupertino, USA).

PCDEQ. Participants were asked to fill out the Psychological Characteristics of Developing Excellence Questionnaire (PCDEQ-2) on paper (Hill et al., 2019). Results from previous research showed a different factor structure for young and older athletes (Laureys et al., 2021); the youngest age group (9 – 12.99 years old) were assessed with the PCDEQ-Child version (PCDEQ-C). The longer version of the questionnaire, PCDEQ- version 2 (PCDEQ-2), was used in the older age groups (from 13.00 years onwards; Hill et al., 2019).

Data analysis. For both EF and PCDE the factor scores are different for younger and older gymnasts. For EF, the raw CBS scores were converted into weighted sum scores based on previous structural equation modelling analyses in Laureys et al. (2022). In this study, using the same age range and the same test battery as in the current study, it was found that for the younger age group (until 12.99 years old), a unitary construct 'EF' was the best fitting model. During adolescence (from 13.00 years old onwards) EF specialises into four separate components. The best fitting model, the four-factor model includes the three core executive functions as described by Miyake and colleagues (Miyake et al., 2000) (working memory, inhibition, shifting) and adds planning as a fourth component. Both the sum scores of the unitary and four-factor model were calculated based on the model and loadings as described in Laureys and colleagues (2022), which can be found in Supplementary Material 3. For the PCDEQ factors there is also a distinction between 9-12.99 years old and the older gymnasts. As the athlete grows older, the set of psycho-social skills and behaviours will increase in number and difficulty, as the demand of the environment will increase in difficulty as well (Blijlevens et al., 2018; Drew et al., 2019). The PCDEQ-C used for the younger gymnasts consists of 51 items, leading up to a 5 factor structure (Laureys et al., 2021). These factors consist of 4 adaptive factors (Imagery and Active Preparation, Self-Directed Control and Management, Seeking and Using Social Support), 2 maladaptive factors (Adverse Response to Failure, Performance Worries) and 1 dual-effect (Performance Worries). For the two older age groups the PCDEQ-2 was used with 81 items, leading to 7 factors (Hill et al., 2019). The PCDEQ factors consists of 3 adaptive factors (Imagery and Active Preparation, Self-Directed Control and Management, Seeking and Using Social Support, Active Coping), 2 maladaptive factors (Adverse Response to Failure, Clinical Indicators) and 1 dual-effect factor (Perfectionistic Tendencies). All standardized factors were mathematically rescaled onto a score on 10.

Within the sample of gymnasts (N = 178), we only selected those gymnasts that completed both instruments twice within one year (N = 57). Gymnasts who then did not complete the questionnaire fully, were removed (N = 2). Data from 3 more gymnasts were also completely removed, because there was missing data on the CBS tests because of apparatus malfunction (i.e., loss of internet and therefore data of a specific EF task was not saved on the server). This led to us retaining the data of 52 gymnasts, with complete data on both the CBS and PCDEQ test batteries and without outliers.

Statistical analysis. First, two repeated measures ANOVAs were used to check the development of both EF and PCDE between all stages in the one-year time period (time x stage). Therefore, a one-factor score was made for EF and the PCDE for all stages. The EF one-factor score is the weighted sum score for -13 years old, used for all stages. For the one-factor score for PCDE, again the factor structure of the -13 years old was used for all stages, consisting of a mean score of the 5 factors, with a reverse scoring for the maladaptive factors. Significant interaction and main effects were further examined with Bonferroni post hoc tests. Effect sizes were calculated as omega squared (ω^2); ω^2 sizes between 0.01 and 0.06 are considered small effect, sizes between 0.06 and 0.14 are considered a medium effect, sizes above 0.14 are considered a large effect (Goss-Sampson, 2019).

Next, repeated measures ANOVAs analysed differences over a one-year time period per EF component and PCDEQ factor consistent with their age group, within gymnasts who stayed in the same stage and gymnasts who transitioned stages (time x group). For significant main effects of time, post-hoc paired samples t-test, were conducted to see how the various EF components or PCDEQ factors developed over time within a specific talent stage. All data were analysed using JASP Version 0.16.03 (2022).

For the last part of this study, case studies of all junior-to-senior and senior gymnasts were compared to observe to what extent variability in EF and PCDE development was still apparent at these later stages. Difference scores were then calculated for each gymnast, a delta score where the score of the second test occasion was subtracted from the first test occasion (T_2-T_1). These difference scores were plotted in a bar chart, to visualise inter-and intrapersonal differences for both EF and PCDEQ factors. Furthermore, the minimal detectable change (MDC) was calculated, by first computing the intraclass correlation coefficient (ICC) and the standard error of measurements. The following formula was then applied to estimate MDC, where SD_{baseline} is the standard deviation at baseline (Chen et al., 2012):

$$SEM = SD_{baseline} * (\sqrt{1 - ICC})$$

$$MDC_{90} = 1.96 * (SEM) * \sqrt{2}$$

Results

1A. One-factor changes

First, two repeated measure ANOVA's (time x stage) for EF and PCDE were analysed. For EF, results showed an interaction effect of stage and time ($F_{(1;47)} = 7.546$: $p < 0.001$; $\omega^2 = 0.10$ and $F_{(1; 46)} = 16.123$; $p < 0.001$; $\omega^2 = 0.08$; respectively). Scores on EF improved over time for the youngest stage (aspiring); however, the scores for the gymnasts at the older stages (from the junior stage onwards) stayed the same (see Figure 1). Table 2 shows the group means and standard deviations in more detail, as well as the significant differences between stages. For PCDE, there was neither a significant interaction effect of time*stage ($F_{(1;47)} = 0.614$; $p = 0.654$; $\omega^2 = 0.00$), nor a significant main stage ($F_{(4; 47)} = 0.553$; $p = 0.689$; $\omega^2 = 0.00$) or time effect ($F_{(4; 47)} = 1.638$; $p = 0.207$; $\omega^2 = 0.002$).

*** Insert Table 2 and Figure 1 ***

1B. Changes per EF component and PCDEQ factor

Results from the youngest group will be discussed first. The repeated measures ANOVA for EF showed that in the youngest group, there is a significant main effect of time. No significant effects emerged for the PCDEQ factors (Table 3). Paired samples t-tests, showed an increase in EF score over time for both the aspiring group test ($t = -4.036$, $p < 0.001$, Cohen's $d = -0.903$) and the aspiring-to-junior group ($t = -3.074$, $p = 0.012$, Cohen's $d = -0.927$). Figure 2 shows the means at time point 1 and 2 per stage and per EF component and PCDEQ factor.

*** Insert Table 3 and Figure 2 ***

Next, in the older groups, the repeated measures ANOVA demonstrated a significant effect of time for inhibition and planning, and a significant interaction effect for working memory. Paired samples t-test revealed a significant increase in score for planning ($t = -3.023$, $p = 0.023$, Cohen's $d = -1.144$ and working memory ($t = -2.777$, $p = 0.032$, Cohen's $d = -1.050$) in the junior stage. The senior stage only had a significant difference for working memory (t =

-2.772, p = 0.032, Cohen’s d = -1.048), although this was a decrease in score over time. No significant effects were found for the PCDEQ factors (Table 4). Figures 3 and 4 depict the means per stage for each EF component and PCDEQ factor at time point 1 and 2.

*** Insert Table 4 and Figures 3 and 4 ***

1C. Case study approach

Although the paired samples t-test did not show significant differences over time for the older groups, variability in development for the EF components and PCDEQ factors was observed between individuals. The difference score was a delta score where the score on each EF and PCDEQ factor of the second test occasion was subtracted from the first test occasion (T2-T1). Table 5 also gives more information on the proportion of gymnasts increasing, decreasing or remaining a steady-state score. This is based on which gymnasts’ delta score differentiate from the MDC calculations per variable.

*** Insert Table 5 ***

Figure 2 visualises the difference scores on EF components and PCDEQ factors for the seven artistic gymnasts of either the junior-senior or senior group. A general improvement on the four EF components would be preferable, and one gymnast indeed showed this pattern (Jun-Sen 3), although working memory does not seem to change over time. All other gymnasts showed a mixed pattern, Jun-Sen 1 for example had an increase in score for shifting but a decrease for planning and working memory, while Sen-Sen 1’s scores increased for inhibition and planning and decreased for shifting. Overall, inhibition increases most over time, and working memory showed to change the least over time, together with the shifting component (Table 5). In contrast, a mixed pattern is found for planning, which seemed to change the most in both directions. Apart from Sen-Sen 1, the senior gymnasts seemed to show smaller changes (i.e., lower delta scores) on all four EF components, compared to the group of junior-to-senior gymnasts.

Ideally, for the PCDEQ factors, a decrease in score should be observed for the negative characteristics (i.e., factor 1 'Adverse Response to Failure' and factor 7 'Clinical Indicators') and an increase on the positive characteristics (factor 2, 3, 5 and 6). This trend is not observed in the junior-to-senior gymnasts, where some indeed have a decrease for one negative PCDEQ factor but an increase in the other (e.g., Jun-Sen 3 and 4) and others also showed a decrease in the positive PCDEQ factors (e.g., Jun-Sen 1, 2). In the senior-to-senior group of gymnasts, there are two gymnasts who seem to align with the 'ideal' trend in scores (i.e., Sen-Sen 1 and 6), but the other gymnasts in this stage showed decreases for positive PCDEQ factors and the other way around. Overall, when the delta scores of all gymnasts are compared, Jun-Sen 2 and 6 are the two gymnasts with the smallest delta scores on all PCDEQ factors. Notably, Jun-Sen 5 is the only gymnasts with a decrease in score on all PCDEQ factors, with a large decrease in score for 'Imagery and Active Preparation'. Generally, the delta scores are rather small, and most gymnasts seem to stay in the steady-state condition (Table X). If there is an increase or decrease in score, it is more likely to be in the junior-to-senior group compared to the senior group of gymnasts. The senior-to-senior gymnasts seemed to have smaller delta scores for Adverse Response to Failure and Perfectionistic Tendencies, but the delta scores on other PCDEQ factors are similar to the junior-to-senior gymnasts in size.

*** Insert Figures 5 and 6 ***

Discussion

The primary purpose of this study was to examine developmental trends in EF and PCDE factors in young male and female artistic gymnasts. Overall, results of this study showed an increase in score for EF over time, although score improvements tended to stagnate during later stages. For PCDE, scores at all stages did not improve over the one-year follow-up. Contrary to what we hypothesized, gymnasts transitioning stages did not show a decline in their PCDE score, but rather remained stable. However, the case studies of junior-to-senior and senior-to-senior gymnasts suggest that, at these stages, there still is considerable developmental variability. This underlines the individual developmental trajectories athletes go through, and urges for more studies using longitudinal designs.

In contrast to what was hypothesised, the EF developmental trajectory of the athletes did not differ from the EF development in a general population. This results was also found in a recent study of Beavan and colleagues (2020) with football players. According the broad-skill hypothesis, it could be possible that domain-general EF performance and development is triggered by their athletic environment and/or non-athletic environment with continuous cognitive challenges. Since our results do not support this hypothesis, this could be an indication that EF develops rather consistent in line with the general maturation of the brain (Barnea-Goraly et al., 2005; Sowell et al., 2003; Yakovlev, 1967). The domain-general EF gradually improved in the younger stages, and performance levelled off during the senior stage, when late adolescence/early adulthood is reached (Anderson, 2002; Huizinga et al., 2006). During the junior stage (adolescence), shifting already stagnated, although other studies found that this continued to develop until early adulthood (Best et al., 2011; Diamond, 2013). This is probably because of the relatively low complexity in this shifting task. The inhibition task in contrast, is a more complex task, documented to keep increasing at later ages (Huizinga et al., 2006; Laureys et al., 2022; Miyake et al., 2000), although the performance plateaued at adolescent ages as well. Consistent with results from previous research (Anderson et al., 2001; Huizinga et al., 2006), performance on the planning and working memory tasks increased during the junior stage and levelled off at the senior (late adolescence/early adulthood) stage. In line with the study of Beavan (2020) and results from the meta-analysis of Kalen et al. (2021), these results suggest that the association between EF and sporting experience is limited, suggesting that practitioners should be careful to include EF in talent identification batteries. It is currently debated whether EF can actually improve performance (Kalen et al., 2021; Simons et al., 2016), and our results align with the idea that the role of EF is limited. Since results here also depict a similar developmental trajectory for athletes compared to the general population, the impact of EF during the talent development pathway is also questionable.

The development of the PCDEQ factors was less pronounced. There was no improvement over time nor between developmental stages when the one-factor PCDE was examined. When the different factors were examined for the gymnasts per stage and the gymnasts transitioning stages, the PCDE scores again seemed to remain stable over time. Research has pointed out, although, that changing stages comes with challenges in both the athletic and non-athletic domain (Morris, 2013). In the case of artistic gymnastics, it could be argued that the aspiring-to-junior transition is possibly the hardest one, instead of the earlier suggested junior-to-senior transition (Stambulova et al., 2009). In Flanders, aspiring-to-junior gymnasts move into boarding school, change training halls and coaches, and have to deal with academic transitions by moving from elementary to secondary education. Besides these demanding (non-athletic) environmental changes, there is also the increase in physical demands (i.e., more training hours), technical demands (i.e., training new, more complex skills) and the biological developmental processes challenging the individual (social, cognitive, psychological, physical development; (Wylleman & Lavallee, 2004). The junior-to-senior transition again comes with both athletic and non-athletic challenges, although these challenges are less ‘sudden’ and more gradually build up (e.g., intensity of practices or increased competition levels) and are accompanied by less academic and/or environmental changes.

Overall, there seem to be no evolution in scores on the PCDEQ factors over time. Previous research has highlighted that the PCDE development should be explicitly taught in order to improve (Dohme et al., 2017). Gymnasts in the current sample were not asked to work and try to improve their own PCDE profile, which could explain the absence of changes over time, although other studies have documented an increase in some PCDE factors (Saward et al., 2020). PCDE scores of adolescent football players improved over a period of 20 months without the involvement of structural learning. A longitudinal study in adolescent football players did observe an increase in some PCDE factors over a 20-month period, without the involvement of structural learning. Another reason could be that the PCDEQ is a self-report questionnaire. Aside from self-bias, there could also be larger amounts of technical error of measurement because of more individual variation, not allowing to find statistical changes over time. Furthermore, the PCDEQ is also a self-perception questionnaire. It is possible that the effect of the transition on the perception on the gymnasts' PCDE skills were already flattened out, because they were measured relatively late after the actual transition. The tests in this study were conducted in the second semester of the year, giving the gymnasts over six months to adjust to the new stage. Furthermore, it is the athlete's own perception of the transition that will determine how facilitative or debilitative they will experience the process (Morris, 2013). Gymnasts transitioning stages for example, are not only expected to meet higher demands by the people and environment surrounding the athlete (push), but they can also enjoy the higher level of quality during practice and competitions (pull). This push-and-pull effect might give the athlete more confidence, perceived competence and/or intrinsic motivation, and thus make the transition process more facilitative (Whitehead et al., 2004). Given the rather high mean scores on the positive PCDEQ factors (see Tables 2 and 4), this could indeed be what the gymnasts here experienced. Future research should try to examine the PCDE as close as possible to the transition from one stage to the other and take into account the athletes' perception of the transition process.

Although little to no developmental changes were found during the later stages in the current sample as a whole, considerable variation was observed at the individual level. For both EF components and PCDEQ factor mean scores were high, although the bar charts showed differences between all gymnasts. This could be an indication that these gymnasts have reached a certain threshold already, leaving room for more individual variation. Most gymnasts still seemed to increase their score in inhibition and variation in both the positive and negative direction was most outspoken for planning. In contrast, shifting and working memory seemed to remain the same over one year during adolescent ages. The variation in delta scores also seemed to be slightly smaller for the senior gymnasts compared to the junior-to-senior gymnasts on the EF component, as in agreement with EF performance levelling off during (late) adolescence (Best & Miller, 2010). For the PCDEQ factors, some gymnasts only had small delta scores, especially the senior gymnasts for the negative factor adverse response to failure and the dual effect factor perfectionistic tendencies. It was also shown that the delta-scores of the gymnasts did not deviate much from the minimal detectable change score, and most gymnasts did not increase nor decrease there score within one year. Nevertheless, scores on the PCDEQ factors seemed to increase or decrease with at least one point on a 10-point scale over one year for most gymnasts. Furthermore, the decrease or increase in score over time was for most gymnasts not in line with what is expected (a decrease for negative factors and increase for positive factors), showing gymnasts are still changing perceptions on their set of PCDE and would probably profit from more structural guidance in developing the right PCDE profile for them. Overall, the bar charts showed both intra- and interpersonal developmental variability, which is again a sign of the complex, non-linear development of talented athletes (Vaeyens et al., 2008). When examining talent development, case study approaches should be used more often, since this is an appropriate design to examine different and changing athlete development trajectories (Cobley et al., 2014).

This study is one of the first to examine cognitive and psycho-behavioural skills in a longitudinal design, while also taking into account individual differences. In this way, the (non-linear) development of cognitive and psycho-behavioural skills in young, elite athletes was tracked. The longitudinal design also provided insight into the deployment of the cognitive and psycho-behavioural skills per talent development stage, and into differences between athletes transitioning stages or staying in the same stage. Future studies in talent identification and development should continue to adopt such longitudinal designs, and elaborate this approach in other types of sport. For practitioners working in a talent development environment, where the main goal should be long-term athlete development, longitudinally tracking and monitoring these skills is highly necessary. Using bar charts with delta scores could be a good approach to interpret individual changing trajectories. By collecting more data on the athlete's progression on these skills, individualised programmes can be initiated or monitored, to meet the athlete's ideal EF and PCDE profile.

Both EF and PCDE assessment tools have their flaws and biases, which should be taken into account. The PCDEQ-2/-C for example could use the perceptions of others surrounding the athlete to further interpret results. Alignment of perceptions of the athlete and peers (e.g., other training mates), his/her parents and/or coach for example, could provide more insight in the results, given the important influence these stakeholders play during the talent development process (Cervelló et al., 2007). It should also be noted that due to the specifics of the talent development setting and other socio-cultural features in this study, results found here may not be transferable to other athlete populations (Drew et al., 2019). More research in other early-specialisation sports and other (non-Western) countries is thus needed, also using longitudinal design (with preferably longer follow-up periods). Lastly, this study only used the athlete's perspective, while this could further be strengthened by also taken into account the coach's and other significant others perspective of the developmental process of the athlete. When coaches and other practitioners take these limitations into consideration, they can track athletes' development of EF and psycho-behavioural skills.

Overall, this study examined the development of EF and PCDE factors in a group of young, talented gymnasts. The first part of the study found that the athletes' EF development trajectory is in line with that of a general population. PCDE scores changed mostly in the earlier stages, and no improvement was seen in the later stages. This suggests to be cautious to include cognitive and psycho-behavioural skills in a talent identification battery. The case study approach, however, showed that there still is a lot of individual developmental variation in the older age groups, especially for the environmental-sensitive psycho-behavioural skills. During talent development, it can be still useful to monitored the cognitive and psycho-behavioural skills for long-term athlete development. However, it is then advised to use and depict individualised delta scores for both EF and PCDE scores. This showcases not only the changing, non-linear cognitive and psychological development within athletes, but also the diverse developmental trajectories between athletes.

Disclosure statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Table 1. Numbers of participating artistic gymnasts per age, stage and sex.

	Male			**Female**			**Total**
	Aspiring	**Junior**	**Senior**	**Aspiring**	**Junior**	**Senior**	
9 yo				4			4
10 yo	8			6			14
11 yo	4			7			11
12 yo	1						1
13 yo					1		1
14 yo		5			4		9
15 yo						1	1
16 yo		2				4	6
17 yo		3					3
18 yo and older			1			1	2
Total	13	10	1	17	5	6	52

The grey zones indicate the age-ranges of the stages per sex.

Table 2. Means and standard deviations per talent stage at time point one (T_0) and time point 2 (T_1) for EF and PCDE.

		T_0	**T_1**		**Total**
EF	**N**				
ASP-ASP	20	16.21 ± 2.23	18.06 ± 1.34	a	17.13 ± 1.53
ASP-JUN	10	16.60 ± 2.00	18.85 ± 1.68	a, b, d, e	17.73 ± 1.36
JUN-JUN	8	18.96 ± 1.40	20.89 ± 1.15	c, d, e	19.92 ± 0.78
JUN-SEN	7	19.21 ± 1.88	19.47 ± 2.67	b, c, d, e	19.34 ± 2.21
SEN-SEN	7	19.96 ± 2.02	19.51 ± 1.67	b, c, d, e	19.74 ± 1.82
Total		17.62 ± 2.47	19.03 ± 1.87		18.32 ± 1.92
PCDE	N				
ASP-ASP	20	5.76 ± 0.75	5.97 ± 0.63		5.86 ± 0.64
ASP-JUN	10	5.94 ± 1.02	5.89 ± 0.86		5.91 ± 0.85
JUN-JUN	8	6.21 ± 0.72	6.24 ± 0.58		6.23 ± 0.51
JUN-SEN	7	5.57 ± 0.82	5.95 ± 0.83		5.76 ± 0.78
SEN-SEN	7	6.00 ± 0.69	6.04 ± 0.77		6.02 ± 0.68
Total		5.87 ± 0.80	6.00 ± 0.70		5.94 ± 0.68

ASP = aspiring; JUN = junior; SEN = senior; EF = executive function; PCDE = psychological characteristics of developing excellence. A mean is significantly different from another mean (i.e., difference between stages) if they have other superscript letters (a, b, c, d, e).

Table 3. Repeated measures ANOVA (Time x Group) for EF and PCDE in the younger groups.

	Time	**Group**	**Time x Group**		**Time**	**Group**	**Time x Group**
EF	F = 24.80 (1 ; 29) p < 0.001 $\omega^2 = 0.22$	F = 1.587 (1 ; 29) p = 0.218 $\omega^2 = 0.01$	F = 0.190 (1 ; 29) p = 0.667 $\omega^2 = 0.00$	**Factor 1** Adverse Response to Failure	F = 0.519 (1; 29) p = 0.477 $\omega^2 = 0.00$	F = 0.108 (4; 29) p = 0.745 $\omega^2 = 0.00$	F = 2.990 (4; 29) p = 0.02 $\omega^2 = 0.093$
				Factor 2 Imagery and Active Preparation	F = 0.399 (1; 29) p = 0.533 $\omega^2 = 0.00$	F = 0.521 (4; 29) p = 0.476 $\omega^2 = 0.00$	F = 2.223 (4; 29) p = 0.147 $\omega^2 = 0.01$
				Factor 3 Self-Directed Control and Management	F = 0.148 (1; 29) p = 0.703 $\omega^2 = 0.00$	F = 0.116 (4; 29) p = 0.736 $\omega^2 = 0.00$	F = 3.186 (4; 29) p = 0.085 $\omega^2 = 0.01$
				Factor 4 Performance Worries	F = 2.296 (1; 29) p = 0.998 $\omega^2 = 0.00$	F = 0.008 (4; 29) p = 0.527 $\omega^2 = 0.00$	F = 2.122 (4; 29) p = 0.156 $\omega^2 = 0.01$
				Factor 5 Seeking and Using Social Support	F = 0.659 (1; 29) p = 0.423 $\omega^2 = 0.00$	F = 0.009 (4; 29) p = 0.924 $\omega^2 = 0.00$	F = 1.389 (4; 29) p = 0.248 $\omega^2 = 0.00$

Table 4. Repeated measures ANOVA (Time x Group) for EF and PCDE in the older groups.

	Time	Group	Time x Group		Time	Group	Time x Group
Inhibition	**F = 9.054** (1 ; 18) p = 0.008 $\omega^2 = 0.06$	**F = 0.451** (2 ; 18) p = 0.644 $\omega^2 = 0.00$	**F = 0.008** (2; 18) p = 0.992 $\omega^2 = 0.00$	**Factor 1** Adverse Response to Failure	**F = 0.431** (1; 18) p = 0.520 $\omega^2 = 0.00$	**F = 0.340** (2;18) p = 0.716 $\omega^2 = 0.00$	**F = 0.464** (2;18) p = 0.636 $\omega^2 = 0.00$
Planning	**F = 5.506** (1 ; 18) p = 0.031 $\omega^2 = 0.12$	**F = 0.650** (2 ; 18) p = 534 $\omega^2 = 0.00$	**F = 2.950** (2; 18) p = 0.078 $\omega^2 = 0.07$	**Factor 2** Imagery and Active Preparation	**F = 2.237** (1; 18) p = 0.152 $\omega^2 = 0.02$	**F = 1.506** (2; 18) p = 0.248 $\omega^2 = 0.02$	**F = 0.020** (2; 18) p = 0.980 $\omega^2 = 0.00$
Shifting	**F = 0.497** (1 ; 18) p = 0.490 $\omega^2 = 0.00$	**F = 0.216** (2 ; 18) p = 0.808 $\omega^2 = 0.00$	**F = 0.707** (2; 18) p = 0.506 $\omega^2 = 0.00$	**Factor 3** Self-Directed Control and Management	**F = 2.971** (1; 18) p = 0.102 $\omega^2 = 0.04$	**F = 2.298** (2; 18) p = 0.129 $\omega^2 = 0.04$	**F = 1.000** (2; 18) p = 0.387 $\omega^2 = 0.00$
Working Memory	**F = 0.125** (1 ; 18) p = 0.728 $\omega^2 = 0.00$	**F = 0.624** (2 ; 18) p = 0.547 $\omega^2 = 0.00$	**F = 5.804** (2; 18) p = 0.011 $\omega^2 = 0.05$	**Factor 4** Perfectionistic Tendencies	**F = 0.004** (1; 18) p = 0.998 $\omega^2 = 0.00$	**F = 0.664** (2; 18) p = 0.527 $\omega^2 = 0.01$	**F = 1.326** (2; 18) p = 0.290 $\omega^2 = 0.01$
				Factor 5 Seeking and Using Social Support	**F = 0.529** (1; 18) p = 0.476 $\omega^2 = 0.00$	**F = 2.893** (2; 18) p = 0.081 $\omega^2 = 0.06$	**F = 1.633** (2; 18) p = 0.223 $\omega^2 = 0.02$
				Factor 6 Active Coping	**F = 4.377** (1; 18) p = 0.051 $\omega^2 = 0.05$	**F = 0.196** (2; 18) p = 0.824 $\omega^2 = 0.00$	**F = 0.723** (2; 18) p = 0.824 $\omega^2 = 0.00$
				Factor 7 Clinical Indicators	**F = 0.345** (1; 18) p = 0.564 $\omega^2 = 0.00$	**F = 0.665** (2; 18) p = 0.526 $\omega^2 = 0.00$	**F = 0.294** (2; 18) p = 0.749 $\omega^2 = 0.00$

Table 5. ICC, SEM, MDC measures and amount of gymnasts increasing, decreasing or presenting no change on the various cognitive and psycho-behavioural components

				Junior-senior group			Senior group			Total group		
	ICC	SEM	MDC	#decreasing	#increasing	#steadystate	#decreasing	#increasing	#steadystate	#decreasing	#increasing	#steadystate
Inhibition	0,756	0,063	0,175	0	5	2	0	5	2	0	10	4
Planning	-0,266	0,991	2,748	2	2	3	0	2	5	2	4	8
Shifting	-0,560	2,240	6,207	0	0	7	0	0	7	0	0	14
WM	0,831	0,460	1,268	1	0	6	1	0	6	2	0	12
	ICC	SEM	MDC	#decreasing	#increasing	#steadystate	#decreasing	#increasing	#steadystate	#decreasing	#increasing	#steadystate
Factor 1	0,901	0,503	1,394	1	0	6	0	0	7	1	0	13
Factor 2	0,644	0,563	1,560	2	2	4	0	1	6	2	3	9
Factor 3	0,488	0,723	2,003	0	2	5	0	0	7	0	2	12
Factor 4	0,766	0,539	1,493	0	1	6	0	1	6	0	2	12
Factor 5	0,549	0,802	2,223	0	2	5	0	0	7	0	2	12
Factor 6	0,533	0,473	1,310	1	1	5	0	0	7	1	1	12
Factor 7	0,565	0,808	2,239	1	0	6	0	1	6	1	1	12

ICC = Intraclass Correlation Coefficient; SEM = Standard Error of Measurement; MTD = Minimal Detectable Change

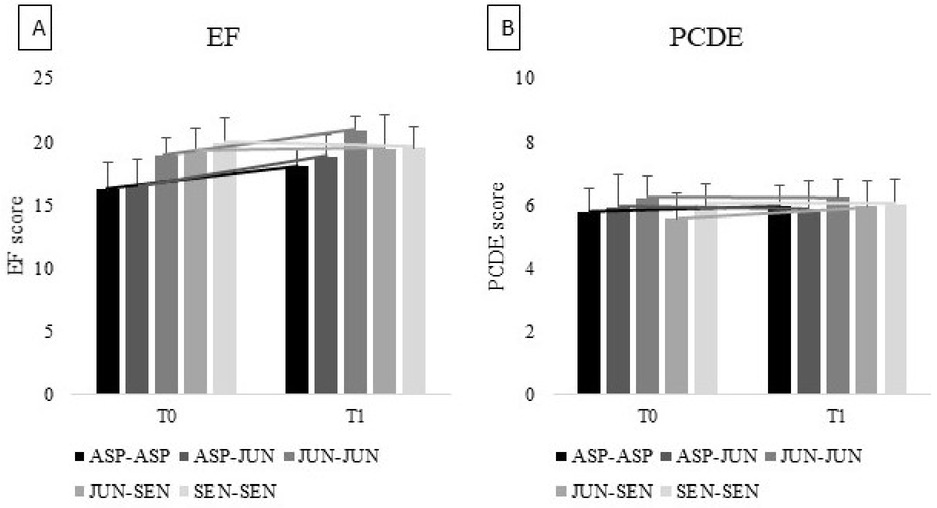


Figure 1. EF (A) and PCDE (B) sum scores over time for the different artistic gymnastic stages. EF = executive functions; PCDE = psychological characteristics of developing excellence; ASP = aspiring; JUN = junior; SEN = senior.

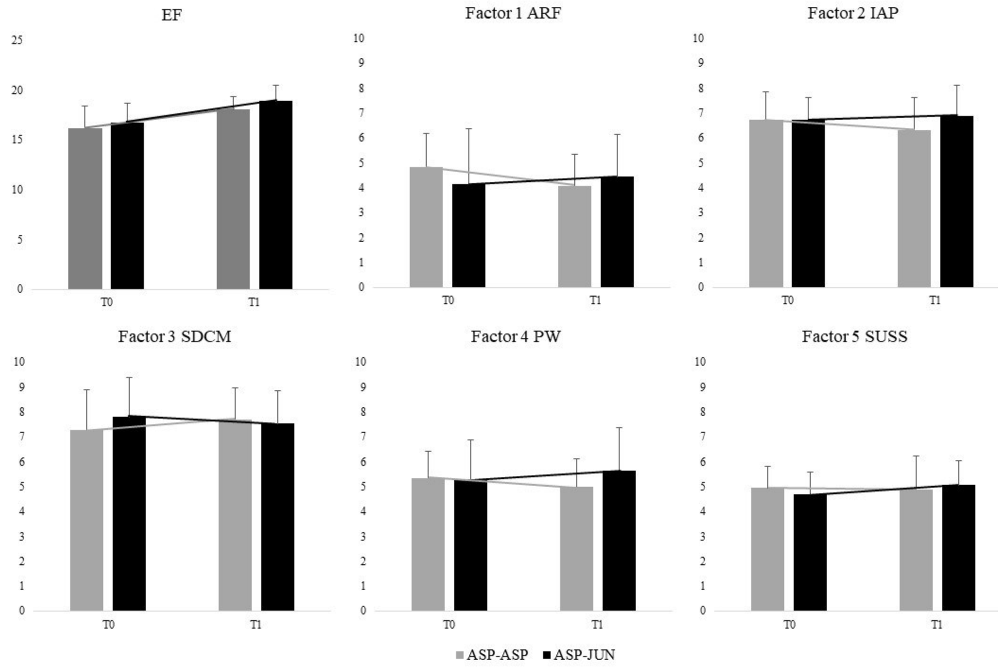


Figure 2. Means and standard deviations per EF and PCDE component on time point one (T0) and two (T1). ASP = aspiring, JUN = junior, EF = executive functions, PCDE = psychological characteristics of developing excellence, Factor 1: Adverse Response to Failure, Factor 2: Imagery and Active Preparation, Factor 3: Self-Directed Control and Management, Factor 4: Perfectionistic Tendencies, Factor 5: Seeking and Using Social Support.

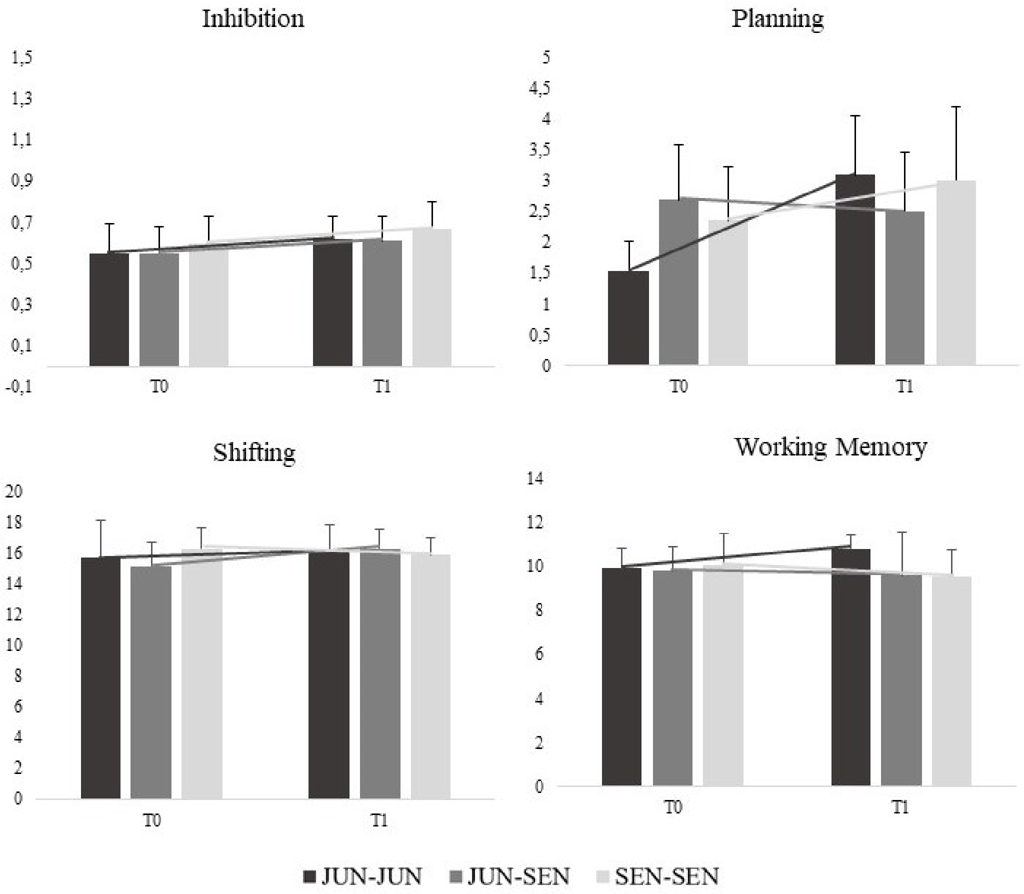
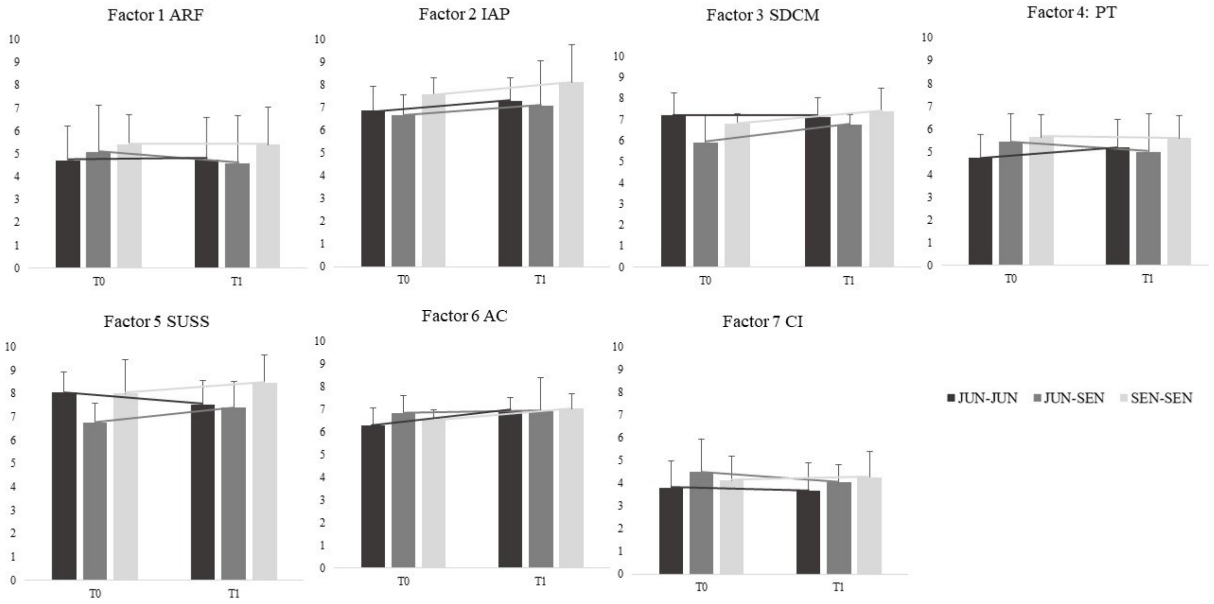


Figure 3. Means and standard deviations per EF component on time point one (T0) and two (T1). JUN = junior, SEN = senior.



Factor 1 ARF

Factor 2 IAP

Factor 3 SDCM

Factor 4: PT

Factor 5 SUSS

Factor 6 AC

Factor 7 CI

Figure 4. Means and standard deviations per EF component on time point one (T0) and two (T1). JUN = junior, SEN = senior, ARF: Adverse Response to Failure, IAP: Imagery and Active Preparation, SDCM: Self-Directed Control and Management, PT: Perfectionistic Tendencies, SUSS: Seeking and Using Social Support, AC: Active Coping, CI: Clinical Indicators.

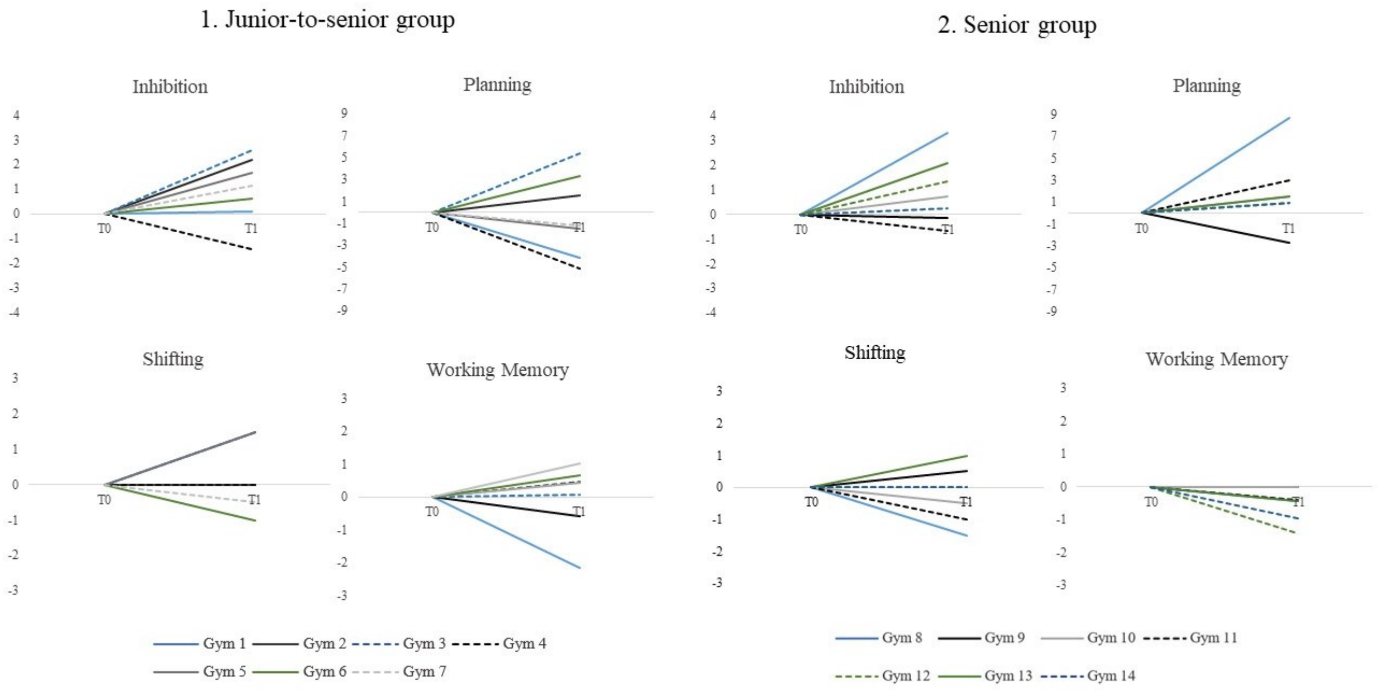


Figure 5. EF components delta scores for seven junior-to-senior gymnast (1) and seven senior-to-senior gymnast (2).

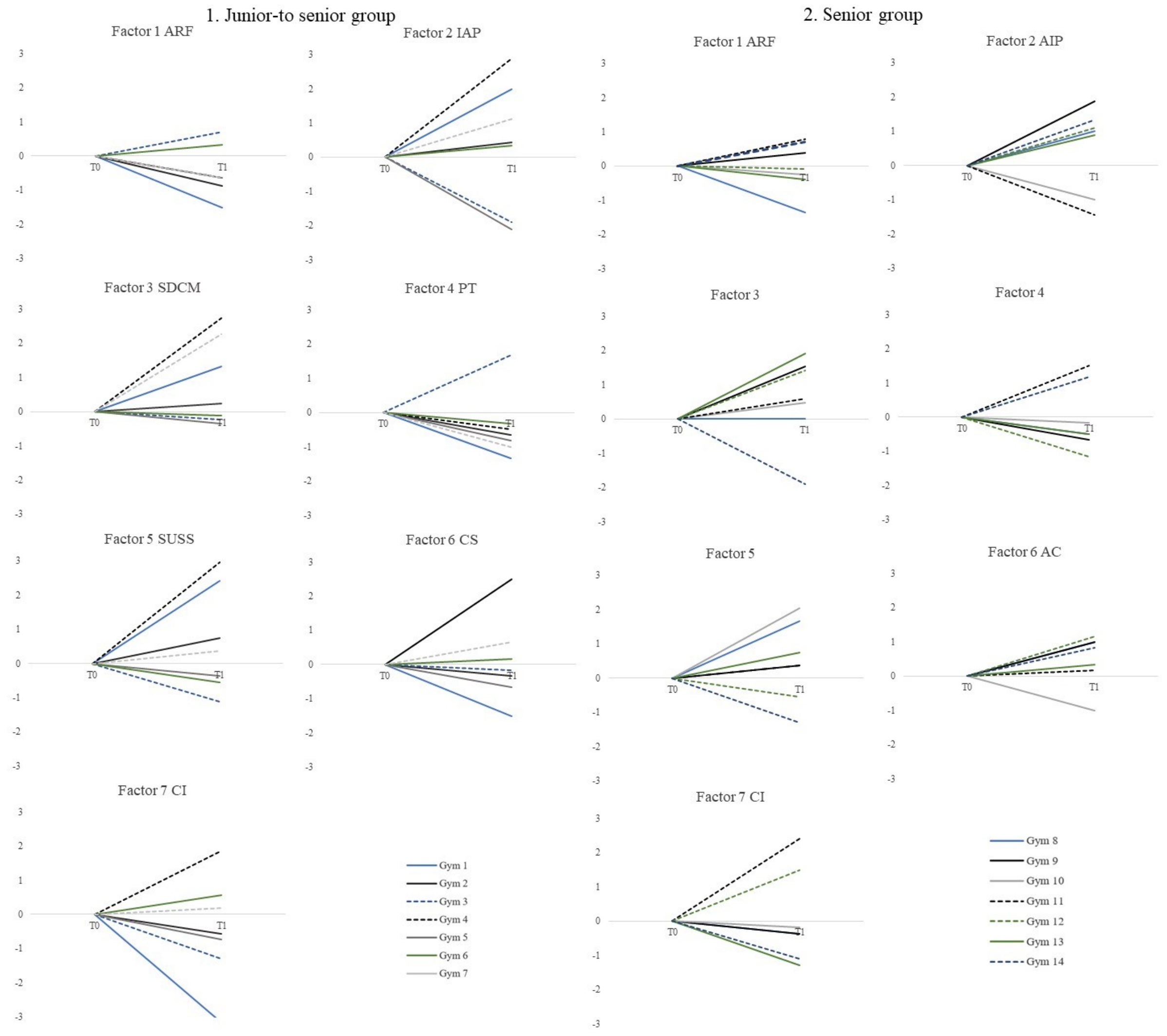


Figure 6. PCDEQ factor delta score for seven junior-to-senior gymnasts (1) and seven senior-to-senior gymnasts (2). ARF: Adverse Response to Failure, IAP: Imagery and Active Preparation, SDCM: Self-Directed Control and Management, PT: Perfectionistic Tendencies, SUSS: Seeking and Using Social Support, AC: Active Coping, CI: Clinical Indicators

Supplementary Material

Supplementary Material 1: Characteristics per artistic gymnastics stage

Characteristics per artistic gymnastics stage

Stage	Characteristics
Aspiring stage	Ages: female: 8-12yo / male: 9-13yo Training hours/week: 16-21h Place: regional centres (7-8 places spread across Flanders) Competition possibilities: regional and national competitions
Junior stage	Ages: female: 13-14yo / male: 14-17yo Training hours/week: 26-28h Place: national centre (Ghent) Competition possibilities: national: Belgian Championship; international: Junior European championships, Junior World Championships
Senior stage	Ages: female: 15+ / male: 18+ Training hours/week: 28-32h Place: national centre (Ghent) Competition possibilities: national: Belgian Championship; international: European Championships, World Championships, FIG World Cup series, Olympic Games

Supplementary Material 2

A detailed overview of the seven CBS tests, used in this study, with the outcome measures where the weighted sum scores for each EF components is based on, and a screenshot of each test (Figure A). Test-retest reliability scores per test were added (Hampshire et al., 2012; Robertson et al., 1997).

Spatial Span (SS) is a task based on the Corsi Block Tapping Task (Corsi, 1972) and measures a persons' ability to remember the relations between objects in space (r = 0.62). This test consists of a grid of 4x4 boxes, that will light up in a random order on the screen. Participants were instructed to tap the boxes in the same sequence as they previously appeared on the screen. The first trial always had a span length of four blocks. When a trial was executed correctly (correct locations in the correct order) the next trial contained one extra box. An incorrect trial was followed with a trial containing one box less. The test ended after three incorrect responses. Response accuracy (SS RA) was used as performance indicator for the spatial span task, and was calculated as the maximum number of blocks remembered correctly for each participant.
Double Trouble (DT) is an adaption of the Stroop test and mainly assesses inhibitory control (Stroop, 1992). Three words are presented to the participant and participants were asked to indicate which of two coloured words at the bottom described the colour of the word at the top (r = 0.92). The test lasted 90 seconds in which participants had to give as many correct responses as possible. For this test, three performance indicators were selected. First, total response accuracy (DT RA) was calculated as percentage of correct trials for each participant. Second, mean response time (i.e. the time between the words appearing on screen and the participants tapping on a word) on double incongruent trials (DT RT II) was calculated for each participant. Double incongruent trials were trials where the top word and target word were different and had a different colour. Third, mean response time on double congruent trials (DT RT CC) was calculated for each participant. Double congruent trials were trials where both top word and target word were the same and had the same colour.
Token Search (TS) is a self-guided search task that mainly assesses spatial working memory (Collins et al., 1998). Participants were presented with a number of boxes randomly placed on the screen and were asked to find a token that was hidden underneath the boxes (r = 0.66). Each box contained the token only once and the next hiding place was unpredictable. The task requires to hold the selected boxes in memory. Selection of an empty box twice or a box that had previously held the token, resulted in a failure. When a trial was executed correctly (all tokens found without error) the next trial contained one extra box. After an incorrect trial the next trial contained one box less. The test ended after three incorrect responses. Response accuracy (TS RA) was selected as performance indicator for the token search task and was calculated as the maximum number of boxes found without error for each participant.
Odd One Out (OO) is a modern adaptation of classical tests of fluid intelligence (Brenkel et al., 2017), and mainly assesses deductive reasoning and shifting. This task consists of nine sets of shapes that differ from each other in colour, shape and size (r = 0.73). The participant had to point out which shape was the most different from the others. A correct response resulted in the next trial being more complex, while an incorrect trial would result in the next trial being less complex. The grade of complexity depended on the amount of variance on the three levels (colour, shape, size) within the nine figures. The test lasted 180 seconds in which participants had to give as many correct responses as possible. Response accuracy as well as response time were selected as performance indicators for this task. Response accuracy for the

odd one out task (OO RA) was calculated as the number of correct attempts for each participant (*N attempts – N errors*). For response time (i.e. time between the trial appearing on screen and the participants tapping on a shape), the mean response time per trial was calculated for each participant (OO RT).

Spatial Planning (SP) is an adapted version of the Tower of London Task (Shallice, 1982), which is primarily used to assess planning ability. Participants were asked to sort balls that are positioned on a tree-shaped frame in numerical order in as few moves as possible, by replacing one ball per move (r = 0.87). The problems became progressively more complex to solve as the participant progressed through the task. The test lasted 180 seconds in which participants had to solve as many problems as possible. Response accuracy was used as a performance indicator for this task and was calculated in two steps. First, trial scores were calculated per trial using the following formula: (*minimum moves required * 2) – moves made*. The total response accuracy (SP RA) was then calculated as the sum of all trial scores for each participant.

Monkey Ladder (ML) is based on a task from the non-human primate literature (Inoue & Matsuzawa, 2007) and mainly assesses visuospatial working memory, or the ability to hold information in memory and to manipulate or update it depending of the purpose or the circumstances. Participants were presented with a number of boxes randomly placed on the screen, with each box containing a number ranging from 1 to the number of boxes (r = 0.57). Participants were asked to memorize the numbers appearing in each box and to tap the boxes in numerical order as soon as the numbers disappeared. When a trial was executed correctly, the next trial contained one extra box. After an incorrect trial the next trial contained one box less. The test ended after three incorrect responses. Response accuracy (ML RA) was selected as performance indicator for the monkey task and was calculated as the maximum number of boxes remembered correctly for each participant.

Sustained Attention to Response Task (SART, (Robertson et al., 1997) mainly assesses inhibition. Participants were presented with single digits in the centre of the screen, each digit appeared for 250 ms (r = 0.76). Participants were asked to respond with a tap on the “GO” button on the screen to each digit (GO) as quickly as possible. However, when the digit “3” appeared on screen (NO GO), participants were asked to withhold a response. Participants had to maintain their attention to this task for four minutes. The response accuracy score (SART RA NG) was calculated as the percentage of correct NO GO trials for each participant.

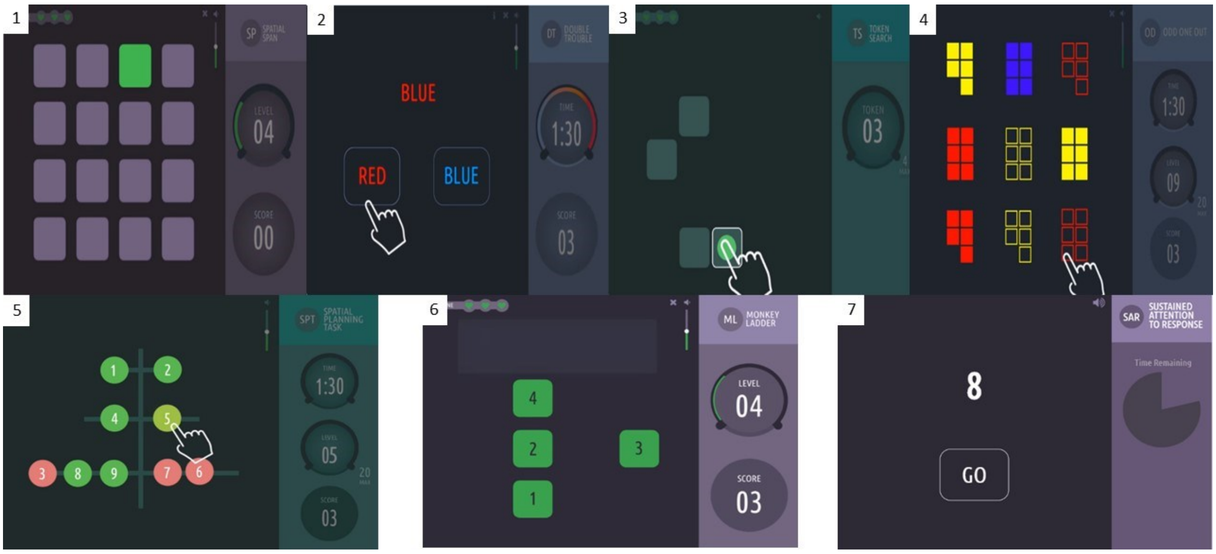


Figure A. Screenshot of the seven CBS tests. 1) Spatial Span, 2) Double Trouble, 3) Token Search, 4) Odd One Out, 5) Spatial Planning, 6) Monkey Ladder, 7) Sustained Attention to Response (SART)

Reliability measures from the CBS

Hampshire (2021) and Robertson et al (1997) have presented information on the test-retest reliability of each test for participants of **12 years and older**, which contains the age range of the adolescents in the current study. These numbers can be found in the table below.

Table S1. Reliability measures on the seven CBS tasks

EF task	R (12+)
Spatial Span	0.62
Double Trouble	0.92
Token Search	0.66
Odd One Out	0.73
Spatial Planning	0.87
Monkey Ladder	0.57
SART	0.76

Although reliability measures provided here were only available for 12 years and older, the large literature database on which these CBS tasks are based (see below) provides strong support that these tests are also suitable and reliable for administration in children between 6 and 12 years old.

While no reliability measures for the specific CBS tasks were available in children younger than 12 years, the large literature database on the tasks on which the CBS tasks are based provides strong support for our claim that the tests used in our test battery are suitable and reliable for administration in children **between 6 and 12 years** old too.

For the Corsi Block task, on which the **Spatial Span** task is based, test-retest reliability has been reported as r = 0.60 for children between 5 and 8 years old (Gade et al., 2017). Since this is very similar to the numbers found in participants from 12 years old onwards for the CBS

Spatial Span task (see table S1), we are confident that in children of 8 to 12 years old, the reliability will also be sufficient. For self-ordered search tasks, such as the **Token Search** task, test-retest reliability of r = 0.70 has been reported in pre-schoolers (3 to 5 years old; Muller et al, 2012), which is again very similar to the reliability measures reported in table S1 for participants from 12 years onwards. Again, this allows us to assume that reliability for this task in children between 6 and 12 years old will also be adequate. Furthermore, Luciana and colleagues (2002) also report on the suitability of tower tasks, spatial span tasks and self-ordered search task from 6 years old onwards (Luciana, 2002). The only working memory task for which we have found no reliability reports in children younger than 12 is the **Monkey Ladder**. However, given its similarity with the other two tasks, it can be assumed that this task too is suitable for administration in children from 7 to 12 years old.

For sustained attention to response tasks, such as the **SART** in our study, test-retest reliability ranges between r = 0.59 and r = 0.70 for 6 to 12 year old children (Servera, 2005). For Stroop tasks, such as the **Double Trouble** task in our study, Penner and colleagues report test-retest reliability values between r = 0.50 and r = 0.80, depending on the type of Stroop task, whether the task was computerized or not, and the performance indicator used, in children with a mean age of 11.4 years old. Furthermore, Homack & Riccio also report on the suitability of Stroop tasks for studies with children (Homack & Riccio, 2004).

For the Tower of London, on which the **Spatial Planning** task is based, a test-retest reliability has been reported of r > 0.70 in children between 6 and 13 years old. Furthermore, as mentioned earlier, the Tower of London is suitable for administration in children from 6 years old onwards (Luciana, 2002). Lastly, for culture fair tests for fluid intelligence, on which the Odd One Out is based, good internal reliability (r = 0.74) is reported for children (Cattell, 1974), with more recent studies in children between 8 and 12 years old consistently confirming the adequate reliability of such tests for this age group (Lee, 2020; Carretti, 2021).

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Supplementary Material 3

This appendix provides additional detail on the model upon which the weighted sum scores for the four executive functions were based, as well as how this weighted sum scores were calculated. In a recent study (Laureys et al., 2022), a confirmatory factor analyses using the same seven tests from this study was performed on a sample of 818 children between 12 and 17.99 years old. The results demonstrated that a four-factor model provided the best fit for this age group with these seven tests (Figure B).

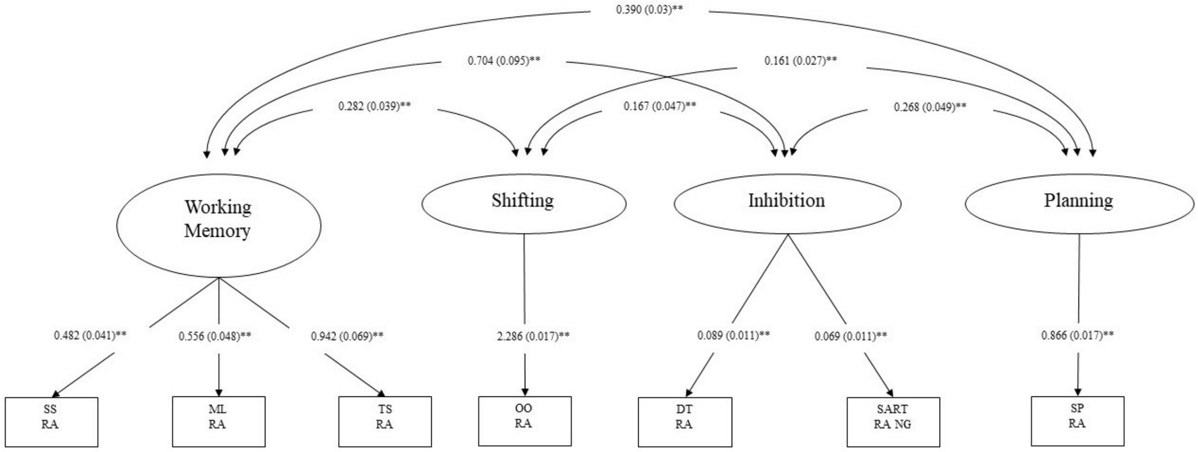

Figure B. Factor structure for the adolescent group. Estimates (standard errors) are displayed (**p < 0.001, * p < 0.05), error variances and residuals are not displayed. SS RA = Spatial Span Response Accuracy; ML RA = Monkey Ladder Response Accuracy; TS RA = Token Search Response Accuracy; OO RA = Odd One Out Response Accuracy; DT RA = Double Trouble Response Accuracy; SART RA NG = Sustained Attention To Response Task Response Accuracy No Go; SP RA = Spatial Planning Response Accuracy. (from Laureys et al., submitted for publication)

This four-factor model also includes standardized loadings for each test to evaluate the relative contribution of each test towards the four EF components, while taking into account the other tests. While the sample in the study of Laureys and colleagues was quite large, and hence allowed this kind of elaborate factor analysis, the sample of the current study was not large enough to do so. Since the sample of the study and Laureys and colleagues (Laureys et al., 2022) is representative for the Flemish youth, and thus the sample of the current study, factor loadings from the study of Laureys and colleagues could be used to calculate a weighted sum score for the four EF components, which best approaches the factor scores that would have been obtained within the original model. Hence, each individual test score was multiplied by their respective standardized factor loading for each EF factor, and then the sum of these weighted scores was calculated. Table A provides an overview of the calculated weighted sum scores with the standardized factor loading for each test.

Table B. Overview of the calculation of the weighted sum scores with the standardized factor loadings for each test.

Inhibition = 0.572*DTRA + 0.266*SARTRANG
Planning = SPRA
Shifting = OORA
Working Memory = 0.441*MLRA + 0.457*SSRA + 0.518*TSRA

DTRA: Double Trouble Response Accuracy; SARTRANG: Sustained Attention to Response Response Accuracy No Go condition; SPRA: Spatial Planning Response Accuracy; OORA: Odd One Out Response Accuracy; MLRA: Monkey Ladder Response Accuracy; SSRA: Spatial Span Response Accuracy; TSRA: Token Search Response Accuracy