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Explaining the high working memory capacity of gifted children: Contributions of processing skills and executive control

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A B S T R A C T

Intellectually gifted children tend to demonstrate especially high working memory capacity, an ability that holds a critical role in intellectual functioning. What could explain the differences in working memory performance between intellectually gifted and nongifted children? We investigated this issue by measuring working memory capacity with complex spans in a sample of 55 gifted and 55 nongifted children. Based on prior studies, we expected the higher working memory capacity of intellectually gifted children to be driven by more effective executive control, as measured using the Attention Network Test. The findings confirmed that intellectually gifted children had higher working memory capacity than typical children, as well as more effective executive attention. Surprisingly, however, working memory differences between groups were not mediated by differences in executive attention. Instead, it appears that gifted children resolve problems faster in the processing phase of the working memory task, which leaves them more time to refresh to-be-remembered items. This faster problem solving speed mediated their advantage in working memory capacity. Importantly, this effect was specific to speed on complex problems: low-level processing speed, as measured with the Attention Network Test, did not contribute to the higher working memory capacity of gifted children.

1. Introduction

Intellectual giftedness is determined by a high level of general intelligence (Thompson & Oehlert, 2010). Intellectually gifted children are usually identified by a standardized intelligence test: in this conception, intellectual giftedness is operationalized as a high IQ (McClain & Pfeiffer, 2012; Warne, 2015; Worrell et al., 2019). High intelligence is not the sole feature of giftedness, however, as it tends to be associated with higher performance in other cognitive abilities. In the literature, intellectually gifted children have repeatedly demonstrated higher working memory capacity than their peers (see Rodríguez-Naveiras et al., 2019 for a meta-analysis). The aim of the current study was to investigate the cognitive processes that could explain their high working memory capacity, as a window both into mechanisms of giftedness, and into mechanisms that can drive individual differences of performance in working memory tasks.

Working memory can be viewed as the workspace of cognition, where we briefly store and manipulate information during cognitive activity (Baddeley & Hitch, 1974). Conceptually, a high working memory capacity is thought to facilitate complex cognitive processing by allowing for the integration of more complex information (Oberauer et al., 2003). Working memory appears to play an important role in learning and education in children (see Cowan, 2014 for a discussion), and is an important predictor of academic achievement (Alloway & Alloway, 2010; Gathercole et al., 2004; Krumm et al., 2008). Working memory spans increase throughout childhood until adolescence, along with cognitive efficiency (Gathercole et al., 2004; Roberts et al., 2018; Thaler et al., 2013).

The literature has often reported on the strong relationship between working memory capacity and the development of high-level cognitive activities, such as mathematical processing (see Raghubar et al., 2010 for a review) and reading comprehension (Daneman & Carpenter, 1980; Nouwens et al., 2016; Seigneuric & Ehrlich, 2005). Working memory capacity is also strongly related to fluid intelligence, in adults (Ackerman et al., 2005), and in children (Giofrè et al., 2013). Some early researchers even argued for an isomophism between working memory capacity and intelligence (Blair, 2006; Kyllonen & Christal, 1990), although this position is currently considered too extreme by the

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majority of researchers (Oberauer et al., 2005). The current consensus is that working memory is the ability to store a limited amount of information and use it in the execution of cognitive tasks (Cowan, 2014); in this sense, working memory can be viewed as one of the processes that contribute to intelligence, defined as the variance shared by cognitive tasks requiring problem solving (Schneider, 2013; for a discussion, see Kovacs & Conway, 2016).

In line with this idea, many studies have shown that intellectually gifted children consistently demonstrate higher working memory capacity than intellectually typical children (Calero et al., 2007; Hoard et al., 2008; Leikin et al., 2013; van Viersen et al., 2014; see Rodríguez-Naveiras et al., 2019 for a meta-analysis). In others words, effective working memory seems characteristic of intellectual giftedness (Hoard et al., 2008; Kornmann et al., 2015; Rodríguez-Naveiras et al., 2019; Vock & Holling, 2008). However, the precise mechanism behind the superior working memory capacity of gifted children is unknown.

1.1. *Determinants of working memory capacity*

What process(es) could lead gifted children to perform better in working memory tests? While determinants of working memory capacity in the general population are relatively well-known, the correlation between IQ and working memory capacity tends to decrease as intelligence increases (Alloway & Elsworth, 2012; Reynolds & Keith, 2007), suggesting that individual differences in working memory capacity may behave differently in gifted children. Besides, gifted children have a specific developmental trajectory, with specific cognitive and non-cognitive characteristics (Morelock & Morrison, 1999; Steiner & Carr, 2003; Vaivre-Douret, 2011), leading to several possible causes for their higher working memory capacity. Indeed, intellectually gifted children have advanced performance in language and memory given their chronological age (Kerr & Multon, 2015; Porath, 2006; Vaivre-Douret, 2011). Some authors have also argued that intellectually gifted children have specific patterns of brain development (Ma et al., 2017; Mrazik & Dombrowski, 2010; Solé-Casals et al., 2019).

In contrast with short-term memory, working memory involves both storage and control mechanisms. This has led some authors to consider that working memory performance results from the combination of short-form memory and executive control components (Baddeley, 2000; Barrouillet et al., 2004; Engle et al., 1999; Logie, 2011; see Cowan, 2017 for a review). Indeed, executive control is essential to inhibit irrelevant information and switch attention between to-be-remembered items and concurrent processing (Kane & Engle, 2003). Although the executive control system encompasses several functions such as inhibition, updating or set shifting (Friedman & Miyake, 2017), models of working memory capacity usually focus on inhibition of interference as a key contributor to working memory (see Kane et al., 2001; Kane & Engle, 2003).

Executive control has long been considered one of the main determinants of working memory capacity, and a major contributor to its relationship with high-level cognition (McCabe et al., 2010; Unsworth & Spillers, 2010), although storage in short-term memory is also an important part of working memory capacity which may contribute to its predictive utility (Unsworth & Engle, 2007a, 2007b). Individual differences in working memory capacity are consistently related to executive control, both in young adults (e.g. Redick & Engle, 2006) and in typically developing children (Cowan et al., 2005). In parallel, intellectually gifted children seem to outperform typical children in tasks involving executive control (Arffa, 2007; Duan et al., 2009; Liu et al., 2011a, 2011b). These findings suggest that efficient executive control could explain their high working memory capacity, although to our knowledge no study has evaluated both executive control and working memory capacity in gifted children.

Although the importance of executive control for working memory is well-established in the literature, other factors influence working memory capacity and could contribute to the higher performance of gifted children. One of these factors is the ability to quickly solve the simple problems that make up concurrent processing requirements in working memory tasks (Unsworth et al., 2009). Indeed, working memory capacity is often measured using complex span tasks (Conway et al., 2005; Redick et al., 2012; see Wilhelm et al., 2013 for a discussion of other paradigms), which require both storage of simple stimuli (such as a letter or a digit) and concurrent processing (such as reading a sentence or solving a simple operation). To succeed in such a task, it is not only necessary to memorize a series of to-be-remembered items as effectively as possible; it is also necessary to perform the concurrent processing tasks as quickly as possible so as to leave time for the refreshing of memory traces (Barrouillet et al., 2004). Due to this aspect of working memory tasks, a greater efficiency in simple problem solving could thus increase working memory capacity. Problem solving speed is a good candidate for the higher performance of gifted children. Indeed, response time for solving simple problems consistently demonstrates a negative relation with intelligence scores (Becker et al., 2016; Goldhammer & Entink, 2011); gifted children tend to solve simple problems faster than nongifted children (Neubauer, 1990), and overall demonstrate a greater capacity solving problems (Vogelaar et al., 2017; Vogelaar et al., 2019).

Note that the ability to solve problems quickly is conceptually distinct from processing speed (Nettelbeck et al., 1986; Neubauer, 1990): the speed of information processing is usually defined as the ability to perform very simple tasks, such as choice reaction time (Sheppard & Vernon, 2008). Although some studies have also shown a relationship between processing speed and intelligence (see Sheppard & Vernon, 2008 for a review), the concept of processing speed is not clear and unitary (Danthiir et al., 2005) and tends to refer to tasks of a lower level than the problem-solving required by concurrent processing in complex span tasks. However, an advantage for this low level processing speed could also conceivably contribute to the higher working memory capacity of gifted children (see Fry & Hale, 2000).

1.2. *Rationale for the present study*

Prior studies have shown that working memory capacity is very high in intellectually gifted individuals (see Rodríguez-Naveiras et al., 2019 for a meta-analysis), but no studies have explored the cognitive processes that can explain this high working memory capacity. The overarching goal of the current study was to investigate in detail the performance of intellectually gifted children in complex span tasks and to explore the possible sources of their high working memory spans. Given that executive control is often regarded as the main determinant of working memory capacity (McCabe et al., 2010) and seems to be more effective in gifted children (Duan et al., 2009; Liu et al., 2011a, 2011b), our primary hypothesis was that executive control would drive the working memory capacity of these children. Because gifted children demonstrate higher capacity for solving problems (Vogelaar et al., 2017; Vogelaar et al., 2019), we also examined the effect of speed in solving the simple problems involved in complex span tasks on the working memory capacity of these children, also controlling for simple processing speed.[1]

Another central aspect of the present study was the method for assessing working memory capacity. Although most working memory tasks are verbal or visuo-spatial in nature, working memory actually constitutes a domain-general construct (Kane et al., 2004). As a consequence, the recommended way to measure working memory capacity is to combine multiple working memory tasks so as to obtain a single score limiting the influence of task-specific factors (Foster et al., 2014; Gonthier et al., 2015). This approach was adopted in the present study. Another important point is that prior studies have measured working memory capacity in gifted children using an ascending procedure:

[1] We thank an anonymous reviewer for suggesting this analysis.

participants begin with moderately difficult trials, the number of to-be-remembered items increases progressively, and the task is cut short when the participant fails a certain number of trials (Hoard et al., 2008; Kornmann et al., 2015; van Viersen et al., 2014). This ascending order of difficulty poses several problems when assessing the abilities of extreme groups such as intellectually gifted children. High-ability children must succeed on in many easy trials before reaching an appropriate level of difficulty. Thus, the ascending order of difficulty can cause fatigue and frustration for high-ability children (e.g. Vandierendonck et al., 1998). These issues can lead to underestimation of working memory performance in intellectually gifted children. In this type of task, participants with high working memory capacity can fail at the easy trials out of boredom (see Gonthier et al., 2017 for a detailed discussion of these issues). Ceiling effects are also a recurring issue in the context of intellectual giftedness (McCoach et al., 2013; Vock & Holling, 2008). To obtain an appropriate measure of working memory capacity, suitable for both typical and gifted children, we developed an adaptive, multimodal complex span task (Gonthier et al., 2017), which was used in the present study.

Prior studies of executive control in gifted children have used specialized experimental paradigms in the context of electrophysiological studies (Duan et al., 2009; Liu et al., 2011a, 2011b). By contrast, we elected to base the present study on the widespread tripartite model of attentional functioning and the corresponding experimental paradigm. Executive control can be viewed as an attentional network coexisting with two other independent attentional networks (Petersen & Posner, 2012): alerting, defined as achieving an alert state, and orienting, defined as the orientation of attention towards sensory input (Fan et al., 2002). The Attention Network Test (ANT) was elaborated to assess each attentional network separately (Fan et al., 2002). This task requires the activation of all three attentional networks to respond to simple stimuli while ignoring distractors; it does not require high-level reasoning processes, which makes it well-suited to the comparison of gifted and typical children. Note that the ANT measures the effectiveness of the executive control network through a particular aspect of executive control, that of resolution of interference (inhibition); this is particularly suited to a study of working memory given that inhibition of interference is an important component of executive control in the functioning of working memory (Kane et al., 2001; Kane & Engle, 2003).

While flanker tasks in general (Heitz & Engle, 2007; Shipstead et al., 2012; Unsworth & Spillers, 2010) and the ANT in particular (Redick & Engle, 2006; Tourva et al., 2016) have demonstrated a relationship between executive control and working memory capacity in young adults, the ANT has never been used in intellectually gifted children to estimate the efficiency of their attentional networks. Given that gifted children seem to specifically demonstrate better executive control (Arffa, 2007; Duan et al., 2009; Liu et al., 2011a, 2011b), and given that IQ in typical children correlates with executive control network in the ANT (Konrad et al., 2005), we expected the two groups to specifically differ in terms of executive control performance, not alerting and orienting. We also expected executive control performance to contribute to the difference between the two groups in terms of working memory capacity, due to its primary role in models of working memory (McCabe et al., 2010; Unsworth & Spillers, 2010).

In order to test our hypotheses, we used an analysis of mediation to identify the variables that could explain the relationship between giftedness and working memory capacity. Mediation allows to explore a chain of relations between variables (see MacKinnon et al., 2007, for a detailed presentation): it tests whether an antecedent variable affects a mediating variable, which in turn affects an outcome variable. Thus, mediation analysis makes it possible to explore the processes by which intellectual giftedness affects working memory capacity. Mediation analysis does not directly test causal relationships (which requires an experimental design), but it identifies possible variables that can create a causal chain. For example, Unsworth et al. (2009) showed that response time and accuracy of processing in complex spans partially mediated the relationship between working memory capacity and intelligence in young adults; in a similar fashion, our mediation analysis tested to what extent executive control and performance in the problem-solving component of complex span tasks could be the source of the relationship between intellectual giftedness and working memory capacity.

2. Methods

2.1. Participants

A sample of 55 intellectually gifted children (mean age = 11.80 years, SD = 1.36, 22 females) and 55 nongifted children (mean age = 11.89 years, SD = 1.24, 22 females) participated in the study. The groups did not significantly differ in terms of age, $t(108) = -0.18$, $p = .855$, $d = -0.03$. No children had known learning disorders; all had normal or corrected vision, and all were native French speakers. Participants were recruited in elementary and middle schools. The experiment was performed in compliance with local ethics regulations. Signed informed consent was provided by all legal guardians in accordance with the Declaration of Helsinki. Before testing took place, the objectives of the study were explained to the children, who then gave oral agreement for their participation. Sample size was determined by the number of available subjects: all gifted children who could be reached and who agreed to participate were included in the study.

All gifted children were identified prior to inclusion in the study by a clinical psychologist using the Wechsler Intelligence Scale for Children IV (WISC-IV; Wechsler, 2005). The inclusion criterion for children in the gifted group was IQ strictly above 125, corresponding to the 95th percentile. For most of the gifted sample ($n = 45$), a copy of these WISC-IV scores was available to verify the IQ > 125 criterion; for the remainder ($n = 10$), WISC-IV scores could not be retrieved, and the IQ criterion was additionally verified using Raven's Standard Progressive Matrices (Raven et al., 1998). The inclusion criterion for children in the nongifted group was IQ comprised between 85 and 115. This criterion was verified using Raven's Standard Progressive Matrices for all children. The distribution of estimated IQ scores was approximately normal in the gifted (mean IQ = 139.64, SD = 8.27, skewness = 0.08, kurtosis = −0.57) and nongifted groups (M = 103.20, SD = 5.64, skewness = −0.09, kurtosis = −0.84). This identification strategy for gifted and nongifted children is in line with current recommendations (Assouline et al., 2009; Aubry & Bourdin, 2018; McIntosh et al., 2012); note that the use of different intelligence tests for the two groups is not an issue because intelligence scores were never used as a variable in the present study.

2.2. Measures

All the measures and conditions collected in this study are included in the present manuscript.

2.2.1. Working memory

Domain-general working memory capacity was measured with a battery of three computerized complex span tasks, the Adaptative Composite Complex Span (ACCES; Gonthier et al., 2017). This task has demonstrated adequate psychometric qualities based on the classical test theory in a sample of 268 French-speaking children (Gonthier et al., 2017). This includes adequate test-retest reliability for the total score ($r = 0.70$) and concurrent validity with the RSPM ($r = 0.34$, close to the population value of $r = 0.36$; Ackerman et al., 2005). The ACCES is composed of the three most common complex span tasks: the reading span, symmetry span, and operation span (Redick et al., 2012). All tasks follow the same structure: participants have to alternate between solving simple problems, and memorizing unrelated stimuli presented after each problem. At the end of each trial, participants are asked to recall all to-be-remembered stimuli in the same order.

In each trial, to-be-remembered stimuli were presented for 800 ms and followed by an 800 ms inter-stimulus interval. Processing problems to be solved were presented until the participant provided an answer, or until too much time had elapsed (see Unsworth et al., 2005). This maximal allowed time was defined based on participant speed in 10 practice trials: the time limit to solve the problems in the experimental trials was the participant's median time during practice plus 2.5 times the median absolute deviation (with a minimum of 2000 ms and a maximum of 8000 ms). This ensured that the pace of the concurrent problem-solving task was tailored to each child's problem solving ability, presumably limiting the role of response speed (Barrouillet et al., 2009; Gaillard et al., 2011). A preliminary study also ensured that the difficulty of processing problems was appropriate for children (Gonthier et al., 2017).

The reading span task required participants to decide whether sentences are semantically plausible (e.g. "Les violons font des bulles"/ "Violins make bubbles") and to memorize single digits; the symmetry span task required participants to decide whether geometric displays are symmetric and to memorize the location of red squares in a 4 × 4 grid; lastly, the operation span task required participants to decide whether simple equations are correct (e.g., 2 + 3 = 3) and to memorize consonants chosen to be phonetically distinctive in French. For each complex span task, participants first trained to memorize stimuli, solve problems, and do both tasks at once. They then performed 6 target trials. The number of stimuli to remember varied adaptively as a function of participant performance on the previous trial (see Gonthier et al., 2017 for details), with set size ranging from 2 to 8 stimuli to remember in a trial.

Participants performed the reading span, symmetry span and operation span, in this order. Working memory span scores were determined for each complex span as the total number of stimuli correctly recalled in the correct position (Conway et al., 2005). Scores on the three complex span tasks were standardized and then averaged to produce a single, composite working memory capacity score. Accuracy and median response times on correctly answered processing problems in the three complex span tasks were also retrieved for each participant. To ensure that participants performed both components of the complex spans correctly, the data from a subtest were excluded if processing accuracy scores were in the bottom fifth percentile of the sample, and working memory capacity was computed from the other two subtests (Gonthier et al., 2015; Unsworth et al., 2005). This occurred for 18 participants (3 gifted and 15 nongifted children). No participant failed to meet this processing accuracy threshold on two subtests or more.

2.2.2. *Attentional abilities*

The Attention Network Test (ANT; Rueda et al., 2004) was used to estimate the efficiency of three independent attentional networks: alerting, orienting and executive control. The present task was directly based on the classic version of the paradigm (Fan et al., 2002). The stimuli were fish pointing towards the left or right of the screen (as used in the child version of the ANT). The stimuli of the task were retrieved from the author website at this address: https://www.sacklerinstitute.org/cornell/assays_and_tools/ant/jin.fan/. Children were required to indicate the direction of target fish by pressing the left or right arrow keys on a keyboard.

The procedure of the ANT is illustrated in Fig. 1. Each trial represented one of 12 possible conditions in equal proportion: 4 types of cues (no cue, central cue, double cue or valid spatial cue) × 3 types of targets (congruent, incongruent or neutral). Each trial began with a fixation cross displayed for a random duration (between 400 and 1400 ms). One of the four possible cues then appeared for 100 ms. After the disappearance of this cue, only the fixation cross was visible for 400 ms. Lastly, a target fish appeared, either alone (neutral condition) or among other fish pointing in the same (congruent condition) or the opposite (incongruent condition) direction. Children then had to press the button corresponding to the direction of the target fish within a 1700 ms delay. The task began with a training phase of 24 trials, including feedback. Children then performed three experimental blocks of 96 trials without feedback, with a 5-second break between each block.

For each participant, average error rate (ER) and median response times (RT) were recorded for each condition. Response times were considered only for correct trials; RTs faster than 200 ms or slower than 1700 ms were considered as anticipation and omission errors and excluded from the computation (approximately 0.56% of trials).

Each attentional network score was determined by the subtraction method for each condition (Fan et al., 2002; Rueda et al., 2004): (1) alerting was estimated by subtracting the no cue condition from the double condition; (2) orienting was estimated by subtracting the central cue condition from the valid cue condition; (3) executive control was estimated by subtracting the incongruent condition from the congruent condition. These three scores were computed separately for RTs and ER. Average error rates over all trials were also retrieved, as well as median response times over all trials, which served to index low-level processing speed.

Reliability was computed for each attentional network score using the permutation method (see MacLeod et al., 2010 for a detailed description). Each participant's data was randomly split 1000 times, and split-half reliability was computed for each of these permutations, then corrected with the Spearman-Brown formula. The reliability of each attentional network score referred to the average of these 1000 split-half

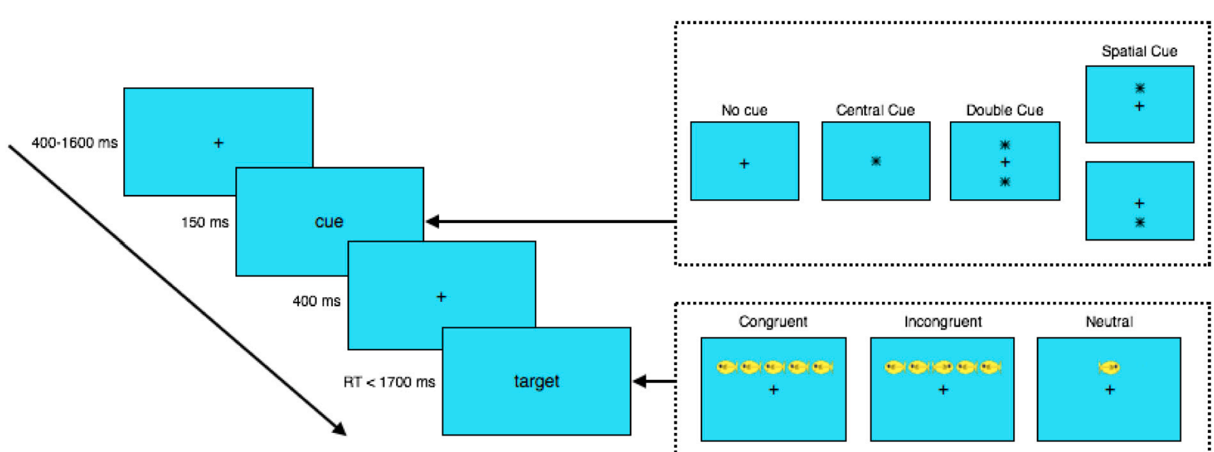

Fig. 1. Procedure for the Attention Network Test.

estimates. For RT, executive control was the most reliable network ($r_{split\text{-}half}$ = 0.52), followed by alerting ($r_{split\text{-}half}$ = 0.36) and orienting ($r_{split\text{-}half}$ = 0.33). For ER, the executive control also had substantially higher reliability ($r_{split\text{-}half}$ = 0.67) than the alerting and orienting scores (respectively, $r_{split\text{-}half}$ = 0.08; $r_{split\text{-}half}$ = −0.23). Although these reliability coefficients are low, they are very close to the results of prior literature using the ANT, which generally demonstrates limited reliability (see MacLeod et al., 2010).

2.3. Procedure

Participants performed the experiment collectively in two testing sessions. The sessions were separated by no more than one week. During the first session, children performed the ACCES and ANT tasks. The ACCES took on average 35 min and the ANT approximately 20 min. During the second session, all children performed the RSPM within a limited time of 30 min.

2.4. Data analysis

The data and R scripts needed to replicate the statistical analyses are available on the Open Science Framework platform at https://osf.io/khnb8. A first series of analyses examined whether the gifted and nongifted groups differed in terms of overall working memory capacity, processing times and processing accuracy on the working memory task, and in terms of scores for the three attentional networks. These analyses were performed based on the general linear model, using between-subject ANOVAs and mixed-design ANOVAs (with Greenhouse-Geisser correction when appropriate). Post hoc tests were performed using Tukey's HSD. Effect sizes were performed using eta squared (η^2) for one-way ANOVA and generalized eta squared (η^2_G) for mixed-design ANOVA as recommended by Bakeman (2005).

A second series of analyses examined whether the difference in working memory capacity between the gifted and nongifted groups was mediated by the processing efficiency and attentional network scores. These analyses were based on bootstrap tests for multiple mediation (Preacher & Hayes, 2004, 2008). This method is preferred over the earlier procedure proposed by Baron and Kenny (1986) for mediation analysis, because bootstrapping is a nonparametric approach that does not depend on normality (Efron, 1988; Efron & Tibshirani, 1986); in the case of mediation analysis, this improves both statistical power and the control of type I error rate (see Preacher & Hayes, 2004, 2008) and allows for the test of multiple mediators simultaneously. Applying the Baron and Kenny (1986) steps for each mediator separately gave similar results here. Indirect effects were estimated using the lavaan package (Rosseel, 2012; bias-corrected method with 20,000 bootstrap samples). Bootstrapping provides 95% confidence intervals for direct and indirect effects; an effect is significant at the $p < .05$ level if the 95% confidence interval does not include zero. Indirect effects were estimated based on all available data (i.e. using the full sample for all putative mediators).

3. Results

We performed outlier analyses using Cook's distance (Cook, 1977); no participant was removed as a result. All subjects who participated in the study were included in the analyses. Descriptive statistics for all measures as a function of group are summarized in Tables 1 and 2. The recall performance measures in the three complex span tasks had a distribution close to normal, with no indication of ceiling effects in gifted children. Variances were comparable across groups for all measures.

3.1. Comparison between gifted and nongifted children

3.1.1. Working memory capacity

Composite working memory scores for all children in the two groups are displayed in Fig. 2. A one-way ANOVA on composite working memory capacity scores with group (gifted vs. nongifted) as a factor indicated that intellectually gifted children had significantly higher working memory capacity than nongifted children, $F(1, 108) = 29.82$, $MSE = 0.479$, $p < .001$, $\eta^2 = 0.22$. A repeated measures ANOVA with groups (gifted vs. nongifted) as between-subjects factor and type of task (Reading span, Symmetry span and Operation span) as within-subjects factor confirmed that intellectually gifted children had significantly higher working memory capacity overall than nongifted children, $F(1, 90) = 21.86$, $MSE = 1.42$, $p < .001$, $\eta^2_G = 0.12$, with no significant difference between the three working memory subtests, $F(1.96, 176.57) = 0.52$, $MSE = 0.61$, $p = .594$, $\eta^2_G = 0.003$.

The correlation between composite working memory capacity scores and estimated IQ, computed across the whole sample, was $r(106) = 0.462$, $p < .001$, reflecting a shared variance of 21%. This correlation was higher than usually observed (e.g. Ackerman et al., 2005), presumably due to the larger range of intelligence scores than usually recruited for studies on the relationship between WMC and intelligence. 83% of gifted children were above the average working memory capacity of nongifted children (see Fig. 2).

3.1.2. Performance on processing problems

A one-way ANOVA with group (gifted vs. nongifted) was performed for response times on the processing problems of the ACCES. The main group effect was significant, indicating that gifted children were overall faster when solving problems in the complex span tasks, $F(1, 108) = 5.20$, $MSE = 0.63$, $p = .025$, $\eta^2 = 0.05$.

Likewise, a one-way ANOVA with group (gifted vs. nongifted) was performed for accuracy on the processing problems of the ACCES. The main group effect was significant, indicating that gifted children were

Table 1
Descriptive statistics for all measures collected in the working memory task as a function of group.

Type of measure	Subtest	Gifted					Nongifted				
		n	*M*	*SD*	Skew	Kurtosis	*n*	*M*	*SD*	Skew	Kurtosis
Recall scores	Reading span	55	26.18	5.15	−0.50	0.53	49	21.39	5.98	−0.74	2.51
	Symmetry span	55	19.64	4.42	−0.05	−0.64	49	17.20	4.06	0.14	−0.64
	Operation span	52	26.27	4.43	−0.54	0.50	52	22.52	4.46	−0.47	0.63
	Composite score	55	0.34	0.67	−0.42	0.18	55	−0.38	0.71	−0.21	−0.78
Accuracy on concurrent processing tasks (in % correct)	Reading span	55	0.95	0.04	−0.74	−0.10	49	0.94	0.04	−0.22	−0.57
	Symmetry span	55	0.98	0.03	−1.65	1.82	49	0.97	0.04	−0.74	−0.82
	Operation span	52	0.98	0.03	−1.33	1.29	52	0.96	0.03	−0.35	−0.90
	Composite accuracy	55	0.15	0.51	−0.12	−0.82	55	−0.16	0.71	−0.37	0.34
Median response time on concurrent processing tasks (in seconds)	Reading span	55	2.57	0.65	1.23	1.75	49	2.90	0.65	0.64	0.05
	Symmetry span	55	2.03	0.52	0.60	−0.62	49	2.13	0.47	0.49	−0.34
	Operation span	52	2.10	0.48	0.24	−0.67	52	2.24	0.52	0.70	0.63
	Composite response time	55	−0.15	0.82	0.77	0.53	55	0.19	0.77	0.45	0.16

Table 2
Descriptive statistics for all measures collected in the ANT as a function of group.

Attentional measure		Gifted (n = 55)				Nongifted (n = 55)			
		M	*SD*	Skew	Kurtosis	*M*	*SD*	Skew	Kurtosis
Response time (RT, in ms)	Median RT	639.66	97.06	0.91	1.36	638.12	77.65	0.14	−0.31
	Alerting	26.44	33.11	−0.23	1.30	27.77	29.61	0.66	0.33
	Orienting	47.34	28.79	−0.38	1.25	40.15	34.94	0.16	0.00
	Executive control	85.07	34.62	−0.33	0.11	106.22	25.94	0.13	−0.65
Error Rate (ER, in %)	Average PE	2.97	2.13	1.19	1.47	4.51	2.25	0.36	−0.75
	Alerting	0.00	3.36	−1.30	4.31	1.26	3.14	0.37	−0.32
	Orienting	0.73	2.66	0.32	−0.48	1.39	2.89	0.01	−0.58
	Executive control	3.84	4.49	1.15	0.56	6.76	4.71	0.69	0.99

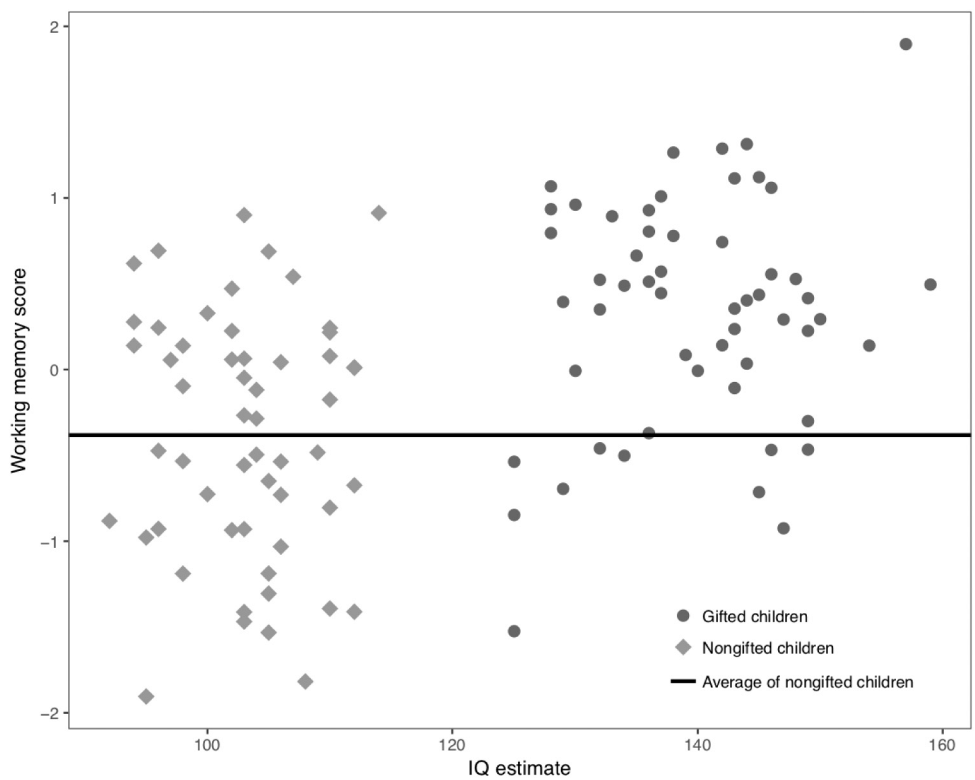

Fig. 2. Working memory scores for gifted and nongifted children.

more accurate when solving problems regardless of the complex span task, $F(1, 108) = 6.83$, $MSE = 0.39$, $p = .010$, $\eta^2 = 0.06$.

3.1.3. *Attentional abilities*

3.1.3.1. Overall attentional measures. One-way ANOVAs with groups (gifted vs. nongifted) as a between-subjects factor were performed on median response times and average error rate (on all trials of the ANT). There was no main effect of group on the overall response time, $F(1, 108) = 0.01$, $MSE = 7724.90$, $p = .927$, $\eta^2 = 0.00$, but gifted children made significantly fewer errors than nongifted children (see Table 2), $F(1, 108) = 13.61$, $MSE = 4.79$, $p < .001$, $\eta^2 = 0.11$.

3.1.3.2. Attentional network scores. We expected gifted children to demonstrate significantly better executive control performance, but not necessarily better alerting or orienting. This hypothesis was tested with a repeated measure ANOVA with group (gifted vs. nongifted) as a between-subjects factor and attentional network (Alerting, Orienting and Executive control) as a within-subjects factor. This analysis was conducted for RT and ER, separately. These results are displayed in Fig. 3.

For RTs, there was no main effect of group, $F(1, 108) = 1.71$, $MSE = 1249.93$, $p = .193$, $\eta^2_G = 0.01$, but group interacted with attentional network, $F(1.98, 213.65) = 6.85$, $MSE = 857.91$, $p < .001$, $\eta^2_G = 0.04$. Post hoc tests using Tukey's HSD showed that gifted children were significantly faster for executive control, $t(312) = 3.54$, $p < .001$, $d = 0.40$, but the two groups did not differ in terms of alerting, $t(312) = 0.22$, $p = .823$, $d = 0.03$, or orienting, $t(312) = 1.20$, $p = .230$, $d = 0.14$. For ERs, there was a main effect of group, $F(1, 108) = 14.99$, $MSE = 14.31$, $p < .001$, $\eta^2_G = 0.05$ and a marginal interaction between group and attentional network, $F(1.79, 193.39) = 2.99$, $MSE = 14.04$, $p = .058$, $\eta^2_G = 0.02$. Post hoc tests using Tukey's HSD suggested that gifted children made significantly fewer errors for executive control, $t(323) = 4.22$, $p < .001$, $d = 0.48$, and marginally less errors for alerting, $t(323) = 1.83$, $p = .069$, $d = 0.21$. There was no difference for orienting, $t(323) = 0.95$, $p = .343$, $d = 0.11$.

3.2. *Determinants of high working memory capacity in intellectually gifted children*

In the previous series of analyses, we showed that gifted children not

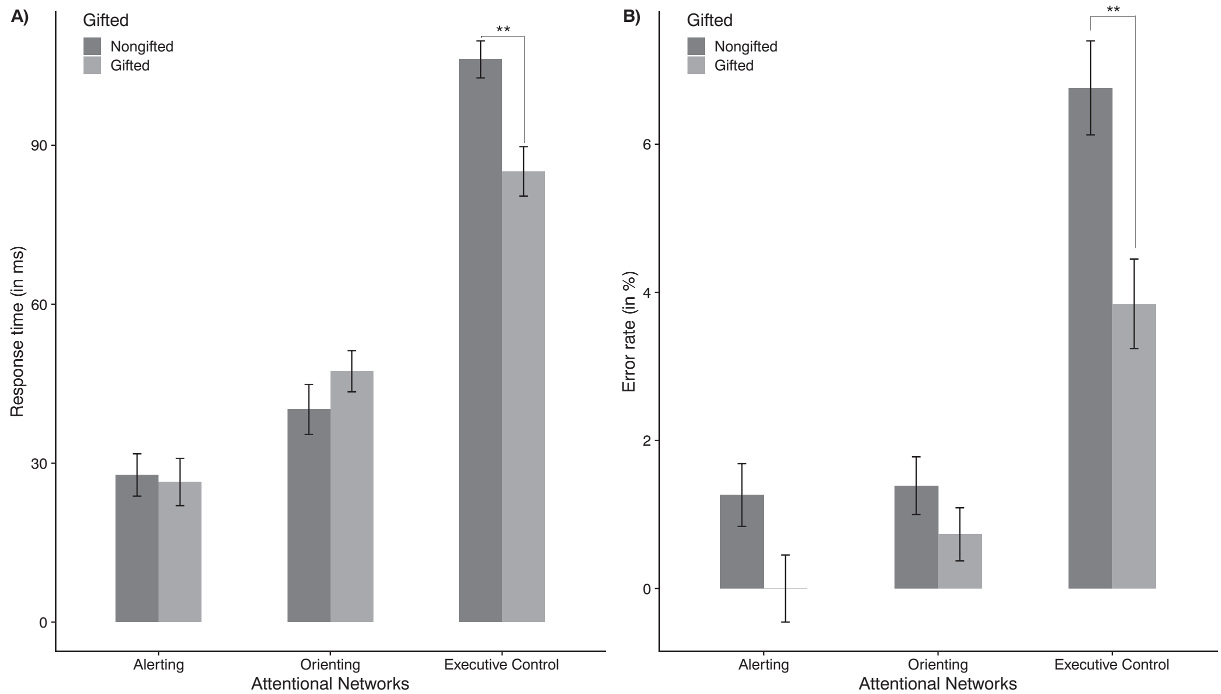

Fig. 3. Performance at each attentional network by group in: (A) response time and error rate (B).

only demonstrated higher working memory capacity; but they were also more proficient in their solving of concurrent processing problems in working memory tasks, and demonstrated better executive control, as suggested by the literature. Examining the pattern of bivariate correlations in both groups (see Table 3) also showed that working memory capacity was negatively correlated with response times in concurrent processing tasks, and with median of RTs from all trials in ANT (see Table 3). All these variables were thus marked as possible mediators of the relation between giftedness and working memory capacity.

In order to investigate the possible source of the higher working memory capacity of gifted children, the final series of analyses investigated all these potential mediators of group differences. The child's group (intellectually gifted vs. nongifted) was treated as the predictor variable and their composite working memory score as the outcome variable. Performance on processing problems of the ACCES working memory task (accuracy and RT, averaged across the three subtests), executive control (ER and RT), and the median RT of all trials on ANT were included as mediators.

As shown in Fig. 4, there was a significant relationship between intellectual giftedness and working memory capacity (Fig. 4A). When controlling for the potential mediators in a multiple regression, the relationship between intellectual giftedness and working memory capacity decreased, but was still significant, suggesting partial mediation (Fig. 4B). This was confirmed by a mediation analysis (Preacher & Hayes, 2004, 2008): the indirect group effect on working memory capacity through the mediators was highly significant (total indirect effect = 0.720, standard error = 0.124, 95% CI [0.480, 0.967]), indicating that group-related differences in working memory capacity were indeed mediated by the selected measures. The direct group effect on working memory capacity was still significant when controlling for the mediators (direct effect = 0.548, standard error = 0.131, 95% CI [0.286, 0.799]), indicating that the mediators did not account for the full extent of working memory differences between groups.

We then examined which of the potential mediators played a significant role in the relation between giftedness and working memory capacity. Executive control, as indexed by both RT and ER, was significantly related only to intellectual giftedness, but not to working memory (Fig. 4B); contrary to our hypotheses, executive control failed to mediate group-related differences in working memory capacity (for RT: indirect effect = 0.030, standard error = 0.040, 95% CI [−0.042, 0.119]; for ER: indirect effect = 0.035, standard error = 0.036, 95% CI [−0.033, 0.113]). Processing speed, indexed as overall response times on the ANT, was related only to working memory capacity, not intellectual giftedness; it also failed to mediate group-related differences in working memory capacity (indirect effect = −0.003, standard error = 0.031, 95% CI [−0.074, 0.053]).

The only significant mediation was observed for processing time on the problems of the ACCES working memory task, which were

Table 3
Correlation between all variables in function of group.

Measure	1	2	3	4	5	6
1. Working Memory Capacity: ACCES	–	−0.05	−0.45**	−0.16	−0.03	−0.44**
2. Performance on concurrent processing tasks: accuracy	0.21	–	0.01	0.05	−0.10	−0.14
3. Performance on concurrent processing tasks: response time	−0.51**	−0.12	–	0.21	−0.24	0.72**
4. Executive control (RT)	−0.18	−0.20	0.19	–	−0.03	0.10
5. Executive control (ER)	0.19	−0.15	−0.25	−0.20	–	−0.34
6. Median overall RT	−0.45**	−0.23	0.63**	0.35	−0.40*	–

Note. $^{**}p < .01$, $^{*}p < .05$; RT: response time, PE: proportion of errors. All *p*-values was corrected by the Holm's method. All correlations above the diagonal were these of gifted children. All correlations below the diagonal were these of nongifted children.

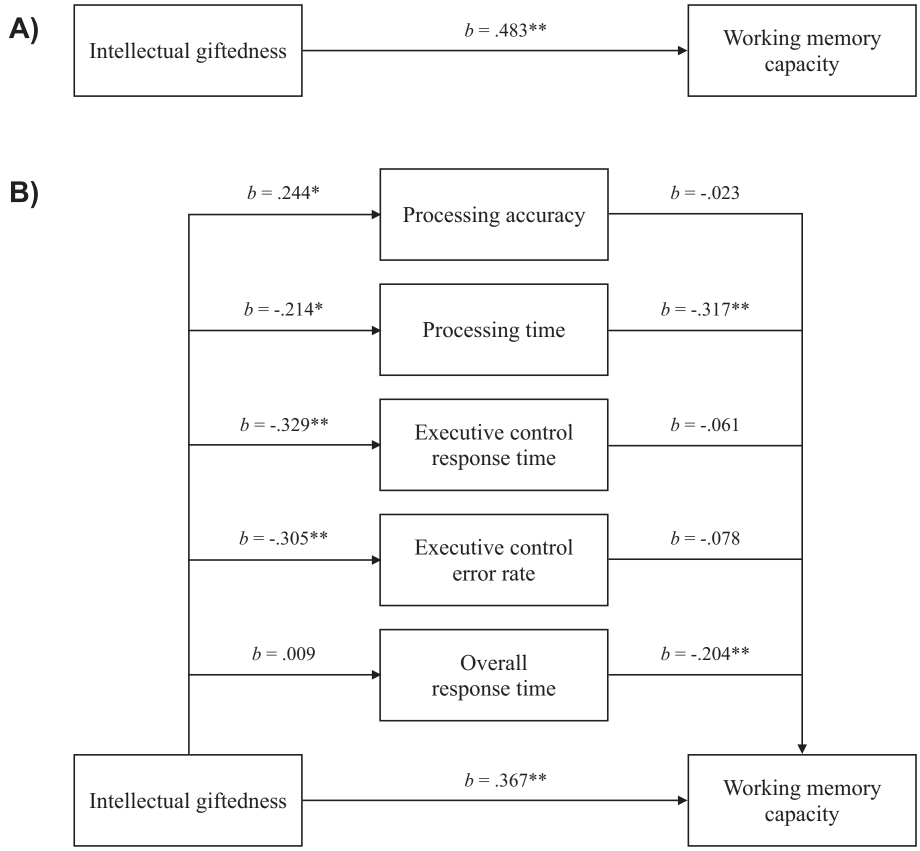

Fig. 4. Relationship between intellectual giftedness (gifted vs. nongifted) and working memory capacity in a simple regression (A) and in a multiple regression analysis, controlling for response time and accuracy in the concurrent processing tasks, response time and error rate in executive control, and overall response speed (B). ***Note.*** * $p < 0.05$; ** $p < 0.01$.

significantly related to both intellectual giftedness and working memory capacity (Fig. 4B). This higher efficiency of intellectually gifted children on concurrent problems partly mediated their higher working memory capacity (indirect effect = 0.101, standard error = 0.051, 95% CI [0.021, 0.229]). Processing accuracy, on the other hand, was related to giftedness but not working memory capacity, and did not significantly mediate the relationship between the two (indirect effect = 0.008, standard error = 0.034, 95% CI [−0.064, 0.076]).

4. Discussion

Previous studies have shown that intellectually gifted children have higher working memory capacity than their peers (Calero et al., 2007; Hoard et al., 2008; Leikin et al., 2013; Rodríguez-Naveiras et al., 2019; van Viersen et al., 2014). The objective of this study was to explore cognitive processes involved in this relationship between intellectual giftedness and working memory capacity.

Among the potential determinants of working memory capacity we investigated, only response time in the concurrent processing task partly mediated the higher performance of intellectually gifted children in working memory. Our results showed that gifted children responded better and faster to the problems in the concurrent processing task. In other words, gifted children responded more quickly to problems in the concurrent processing task without neglecting accuracy. Previous studies have shown that this problem-solving time component partly mediates the relationship between storage and high-order cognition (Engle et al., 1992; Friedman & Miyake, 2004; Unsworth et al., 2009). In the same vein, our findings suggest that problem-solving time partly accounts for the relation between intellectual giftedness and working memory capacity.

These findings are in line with the literature indicating that time spent in the concurrent processing phase is inversely related to recall scores (Barrouillet et al., 2004; Maehara & Saito, 2007; Towse et al., 1998). In this case, the greater speed of gifted children in the concurrent processing task apparently allows them to refresh their memory traces faster, increasing their performance in working memory (Vergauwe et al., 2014). Of course, the mediation analysis performed here cannot definitely establish causality, but the fact that problem solving time mediated the relation between intelligence and WMC makes this the most likely explanation for the working memory capacity advantage of gifted children available at present.

As noted above, this advantage in problem solving speed can be viewed as more efficient problem solving on the part of gifted children (Vogelaar et al., 2017, 2019), rather than a lower-level difference in processing speed (Danthiir et al., 2005): concurrent problems to be solved in a complex span task involve cognitive operations such as sentence verification and arithmetic problems, which can leverage the higher intellectual abilities of gifted children. Our findings confirmed that intellectually gifted children did not respond faster on the ANT than nongifted children, indicating that they do not have a general advantage in terms of low-level processing speed, on this task at least. Thus, the advantage of intellectually gifted children in terms of speed would be moderated by the demands of the task at hand (Geary & Brown, 1991; Lajoie & Shore, 1986). Therefore, intellectual giftedness is not necessarily synonymous with faster performance (Reams et al., 1990). Moreover, low-level processing speed did not mediate the relationship between intellectual giftedness and working memory capacity at all, confirming that the role of problem-solving speed is best understood as a role of the higher ability of gifted children to solve complex problems.

In terms of understanding mechanisms of working memory capacity more broadly, the present study leads to three conclusions. First, the bivariate correlations between WMC and the other measures were highly similar in the two groups of children, confirming that determinants of working memory capacity are comparable in intellectually gifted children and in their nongifted peers. In other words, there does not seem to be a specific mechanism operating in gifted children. Second, executive control did not mediate the higher performance of these children in working memory tasks. Thus, we showed a co-occurrence between an efficient executive control system and a high working memory span in intellectually gifted children, but no direct relation between these two findings. This conclusion is directly opposite to the prediction we had made for the study, and unexpected given previous studies showing a strong relationship between executive control and WMC (Heitz & Engle, 2007; Redick & Engle, 2006; Shipstead et al., 2012; Unsworth & Spillers, 2010). On the other hand, not all previous studies have found this relationship (Friedman & Miyake, 2004; Liefooghe et al., 2008), and executive control is not the sole determinant of WMC performance (Bailey et al., 2011; Dunlosky & Kane, 2007). Our findings reinforce the idea that executive control is not always the most important driver of individual differences in working memory capacity. Third, and conversely, our findings strongly support the importance of time in the processing component of working memory tasks (Barrouillet et al., 2004; Maehara & Saito, 2007; Towse et al., 1998).

Although this was not directly the focus of the present study, it is noteworthy that intellectually gifted children did not substantially differ from their peers in terms of alertness or orientation, but that they were both faster and more accurate for the executive control network. This pattern cannot be explained by a different speed-accuracy trade off in the gifted group, given that gifted children were both faster and more accurate, to a similar extent. These results highlight that intellectual giftedness does not come with better performance for all aspects of attention (Aubry & Bourdin, in press). This characteristic may contribute to the divergence usually observed between parents' and teachers' impressions of the attentional abilities of intellectually gifted children (Rommelse et al., 2017).

4.1. Limitations of our study

Like Unsworth et al., 2009, our results suggest that processing time did not fully account for the predictive power of intelligence, although it did partly explain the correlation with WMC. Among other potential explaining factors, long-term memory store is also an important construct involved in the functioning of working memory capacity (Unsworth et al., 2014; Unsworth & Spillers, 2010). The ability to retrieve items for long-term memory may play as crucial a role as the ability to actively maintain information (Unsworth & Engle, 2007b), and this is a possible research direction that could be explored in future studies.

In addition, the use of memory strategies also contributes to working memory capacity (Bailey et al., 2011; Dunlosky & Kane, 2007), and gifted children tend to use more effective strategies than nongifted children (Gaultney et al., 1996; Harnishfeger & Bjorklund, 1994). Gifted children are also more adaptable in strategy use than their peers (Coyle et al., 1998), and thus could be better able to tailor their mnemonic strategy to the effortful situation of a WMC task. This could involve discovering an effective mnemonic strategy over the first few trials, and then keeping this strategy over the rest of the task (Gaultney et al., 1996). In this case, their higher WMC could be related to expending less mental effort to achieve the same cognitive processing as nongifted children in the working memory task thanks to more effective strategy use. Preliminary data collected in the current study suggest qualitatively that this may be the case, but more detailed investigation would be needed to explore this possibility.

One aspect of the current study that could be improved is measurement of attention. The ANT has the advantage of being a quick assessment of attentional networks performance, and of using stimuli (i.e. flankers and cues) which need low-cost cognitive processing that should not depend on intelligence to a large extent, and it also has the advantage of having a common version that is well-established for use with typical children (Fan et al., 2002). However, our classic version of ANT has some limitations (Callejas et al., 2005; Ishigami & Klein, 2010). The alerting and orienting networks performance were both estimated by cue condition (i.e. no and double cue for alerting; center and spatial cues for orienting). Including a condition specifically dedicated to the estimation of the alerting and orienting networks performance could improve the measure of these two aspects of attentional functioning (Ishigami & Klein, 2010). In addition, the ANT was often perceived as long and boring by the children (Ishigami & Klein, 2015). Although participants demonstrated few omission errors, this boring aspect of this task can have an impact on children's motivation and on the accuracy of attentional measures.

More generally, we based our experiment on one single measure of executive control, but this is a multidimensional construct and the use of multiple measures is desirable to estimate more precisely this type of complex psychological constructs. Although we chose to use the ANT due to its ability to assess three attentional networks in a short time, future research may be interested in using other measures of executive control, such as antisaccade tasks (Friedman & Miyake, 2004; Munoz & Everling, 2004) or go/no-go tasks (Cragg & Nation, 2008). It would also be worth paying particular attention to the psychometric properties of the task: although the temporal stability of the executive control measure in the ANT is considered as adequate, its internal consistency tends to be low, a finding echoed in the present study (MacLeod et al., 2010).

Our study was mainly focused on one of several profiles of giftedness (see Castejón et al., 2016 for details). Indeed, some types of giftedness are associated with particular profiles of working memory performance (Benbow & Minor, 1990; Dark & Benbow, 1994). Moreover, some intellectually gifted children can be underachieving. These children demonstrate a large discrepancy between their high intellectual potential and their academic achievements (Reis & McCoach, 2016). In our sample, all intellectually gifted children had very good school grades. Our findings are thus limited to intellectually gifted children with no academic difficulties, and future research could be interested in gifted children with lower achievements: this population may be more difficult to sample, but they may also demonstrate different patterns of attention and memory performance.

4.2. Summary and conclusions

Intellectual abilities are known to be closely linked to working memory capacity (Ackerman et al., 2005). Although the relation between high IQ and WMC is clearly known, the nature of this relation is unclear. The aim of the current study was to investigate the determinants of the relationship between working memory capacity and intellectual giftedness. Our findings confirmed that working memory capacity is indeed related to intellectual giftedness, and that high working memory capacity is relatively common among gifted children. The current results provided important information by showing that the speed of resolving simple problems involved in working memory tasks contributes to the higher WMC of gifted children, whereas executive control did not appear to play a direct role in this relation. Working memory assessment cannot be viewed directly as a tool for the identification of intellectual giftedness, but it can be used to extend classic intellectual scales such as the Wechsler scales. Assessing cognitive features related to intelligence, beyond IQ itself, also has the advantage of offering a better and more complete understanding of the cognitive profile of each child and its specificities (Acar et al., 2016; Cao et al., 2017), paving the way for better individual support.

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CRediT authorship contribution statement

B.B. coordinated the study. A.A. and B.B. designed the study. A.A. performed the data collection. A.A and C.G. performed all statistical analyses. All authors participated in manuscript redaction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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