Testing a Cognitive Control Model of Human Intelligence

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Testing a Cognitive Control Model of Human Intelligence

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The definition of human intelligence and its underlying psychological constructs have long been debated. Although previous studies have investigated the fundamental cognitive functions determining intellectual abilities, such as the broadly defined executive functions including working memory, the core process has yet to be identified. A potential candidate for such a role might be cognitive control, a psychological construct for the coordination of thoughts and actions under conditions of uncertainty. In this study, we tested a cognitive control model of intellectual ability by examining the association between cognitive control, measured by a perceptual decision-making task and by the attention network test, and general intelligence including components of fluid intelligence (Gf, concerning the ability to solve problems by abstraction) and crystalized intelligence (Gc, related to learning from prior knowledge and experience) measured by the Wechsler Adult Intelligence Scale. We also examined the potential role of cognitive control as a core process involved in another determinant of intellectual abilities, the working memory, measured by the N-back tasks and the working memory complex span tasks. The relationship among intelligence, cognitive control, and working memory was examined using structural equation modeling. Results showed that cognitive control shared a large amount of variance with working memory and both measures were strongly associated with Gf and Gc, with a stronger association with Gf than Gc. These findings suggest that cognitive control, serving as a core construct of executive functions, contributes substantially to general intellectual ability, especially fluid intelligence.

Although intelligence has been thought of as the most prominent property that makes humans unique in the history of biological evolution[1,2], the challenges associated with capturing its ultimate nature[3] have had a signi -cant impact on the consensus regarding its de nition. e early attempt to de ne intelligence was conducted by Charles Spearman[4], who hypothesized the existence of a general factor, *g*, as the core of all cognitive abilities. is unitary conception of intelligence has, however, been challenged by a variety of models of intelligence, including the Primary Mental Abilities[5], the Structure of Intellect[6], and the eory of Multiple Intelligences[7], with all of them proposing that intelligent behavior arises from a collection of factors, e.g., verbal comprehension, spatial visualization, reasoning, and processing speed. ese intellectual abilities have been further synthetized as two components, the uid intelligence (Gf), re ecting the ability to solve problems by abstraction and supported by the multiple-demand system in the brain[8,9], and the crystallized intelligence (Gc), concerning the ability to learn from previous knowledge, with *g* located at the apex of this hierarchical model[10–12]. Most of these theories were derived from a psychometric approach and aimed at quantifying this psychological phenomenon, but this approach has been extensively challenged[13–16] and the process(es) underlying the *g* factor remains unclear.

In contrast to looking for a unique component of intelligence, the triarchic theory of intelligence[16] defines it as comprising three components: the metacomponents, the performance components, and the knowledge-acquisition components. e metacomponents refer to the executive processes involved in problem solving, including mental manipulation and management. e performance components work as the carrier to implement the outcome of metacomponents, i.e., carrying out the actions. e knowledge-acquisition components are associated with the mental processes to obtain new information involving selectively dealing with relevant information and combining various pieces of information[16]. To some extent, the existence of a common element of information processing among these three components is indicated[17], but the nature of this process remains unclear. More recently, the Planning, Attention-Arousal, Simultaneous and Successive (PASS) theory of intelligence[13–15] suggested that intelligence is implemented across a variety of domains and consists of interdependent, but separate, functions supported by di erent brain areas. Speci cally, the process of planning involves executive functions to control and organize behaviors by selecting and constructing strategies, and monitoring performance; the attention-arousal process requires maintaining arousal levels and alertness, and selectively focusing on relevant information; the simultaneous processing and successive processing are responsible for encoding, transforming, and recollecting information. Both the triarchic theory of intelligence and the PASS theory constitute the attempts to embrace both qualitative and quantitative perspectives, and to emphasize the mental processes and operations involved in the intellectual behaviors. Although contemporary theories, whether psychometric or cognitive, have attempted to de ne intelligence in terms of di erent components, it remains unclear whether a unique component is at the basis of these functions, leaving the question about the core process of intelligence open.

In an e ort to solve this puzzled picture, prior work has proposed that working memory, a cognitive function comprising temporary storage spaces entangled with a central executive component in charge of the manipulation of stored information[18–20], might be the psychological core of the Gf[21–23]. Although evidence of a strong relationship between measures of working memory capacity and of the Gf[23–27] exists, this result has been shown to reside on the shoulder of the central executive component only, while the storage component does not seem to correlate with the Gf[28]

Due to the influence of time constraint, i.e., the ET, in responding to the arrow set in each trial, the sampling process can be categorized as either voluntarily terminated (VT) or forcefully terminated (FT). For the VT trials, a response is made when a congruent sample is acquired, which leads to a correct response. Higher CCC, longer ET, and lower information entropy will result in a greater probability of VT trials. The response accuracy on the VT trial depends on the baseline response accuracy (p_0) that can be computed as the average accuracy across all congruent conditions (i.e., the arrow congruency of 5:0). While for the FT trials, response is made by guessing because the arrow set disappears before a congruent sample is acquired, which leads to a random response. The probability of guessing correctly is at chance level ($p_{guess} = 0.5$). The expected response accuracy (E [accuracy]) is computed as the sum of response accuracy on the VT and FT trials using the equation below in which C is a free parameter denoting the CCC. Details and derivations of this equation have been shown in our previous study[46].

$$\begin{aligned} E\,[accuracy] &= 1-(1-P_{group})^{\frac{2^C\times ET}{N_{maj}}}\times p_0+(1-P_{group})^{\frac{2^C\times ET}{N_{maj}}}\times p_{guess} \\ &= p_0-(1-P_{group})^{\frac{2^C\times ET}{N_{maj}}}\times(p_0-p_{guess}). \end{aligned}$$

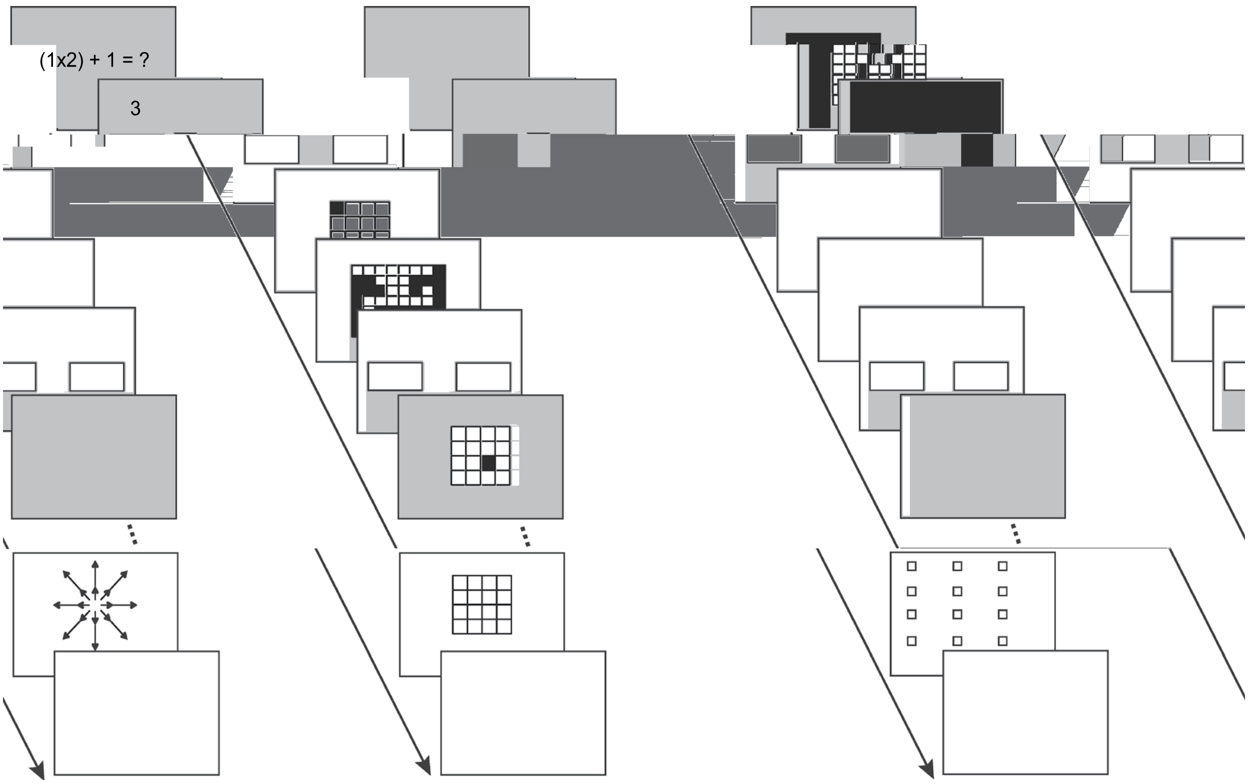
Response accuracy in each condition can be predicted for a given parameter C. The CCC can be estimated as the C value that provides optimal likelihood between the predicted and the empirical response accuracy across all conditions.

The attention network test-revised (ANT-R). In this task, participants were required to identify the direction of an arrow that was flanked by two other arrows on each side. The flankers could point either in the same direction as the target arrow (congruent condition) or in the opposite direction (incongruent condition) of the target arrow. Target and ankers were presented within one of two boxes located either at the right or at the le side of a central xation cross (Fig. 2). In each trial, a visual cue in the form of a 100 ms ashing of the contours of the boxes, was displayed 0, 400, or 800 ms before the target. ere were four cue conditions: double-cue (both boxes ashed, giving temporal but not spatial information about the upcoming target), valid-cue (one of the two boxes ashed, providing temporal and spatial information about the correct location where the target would appear), invalid-cue (one of the two boxes ashed, selecting the alternative location as opposed to the location where the target would be presented), and no-cue (neither of the boxes ashed prior to the target display). Participants were required to respond as quickly and accurately as possible within 1700 ms from the target onset, by clicking either the le or right button on the mouse. e interval between trials varied from 2000 to 12000 ms (mean = 4000 ms). Each trial lasted about 5000 ms on average. ere were 4 blocks consisting of 72 trials in each block, for a total of 288 trials and approximately 30-minute task duration.

Trials with error response or with response time (RT) exceeding 3 SD of the mean RT in each condition (congruent, incongruent) were removed from further analysis. In total, 1.25% of trials were excluded. Mean RT in each condition was then calculated based on the remaining trials, and was used to estimate the executive control (EC) function[55]. e con ict e ect was calculated by subtracting the mean RT of the congruent condition from the mean RT of the incongruent condition. Typically, a more positive con ict e ect suggests lower cognitive control ability. Because we hypothesized that general intelligence would be positively correlated to cognitive control ability, and in order to obtain all positive values of estimates to be included in the SEM, we reversely coded this variable by inverting the terms used in formula, therefore subtracting the mean RT of the incongruent trials from the mean RT of the congruent trials (con ict e ect $= RT_{congruent} - RT_{incongruent}$). us, a less negative con ict e ect indicates higher cognitive control ability. Because the executive control is related to the coordination of thought to guide complex behavior via supramodal mechanisms[45,56], as indexed by the con ict e ect, the EC was included as an additional index of cognitive control in this study.

Measurements of working memory. N-back tasks (spatial and verbal) and working memory complex span tasks were used to measure di erent aspects of working memory. e N-back tasks assess the ability of challenging control over familiarity-based responding[60], or recognition-based discrimination processes[61]

Spatial and verbal N-back tasks. Participants completed a spatial and a verbal N-back task sequentially. In the spatial N-back task[62], four gray boxes were located above, below, to the le , and to the right of a central xation cross (see Fig. 3a



the number of letters correctly recalled, the number of committed errors in solving the math problems, and the cumulative accuracy of math problems were presented.

In each trial of the RotSpan task (Fig. 4b), three to seven arrows appeared sequentially, being either short or long in length and pointing towards one of eight possible directions. Before the presentation of each arrow, a distracting task was presented, which required participants to judge whether a rotated letter was presented in its normal configuration (e.g., R) or backwards (mirrored). After all of the arrows were presented, participants were asked to recall them with the correct length and direction, and in the order they were presented by sequentially selecting the arrows on the response screen. Feedbacks including the number of arrows with correct length and direction that were successfully recalled, the number of errors regarding letter rotation, and the cumulative accuracy of letter-rotation task were presented.

In each trial of the SymSpan task (Fig. 4c), two to five red squares appeared sequentially and at different locations (one of sixteen possible locations on a 4 × 4 grid). Before the presentation of each square, a distracting task required participants to judge whether a picture was vertically symmetrical or not. At the end of a trial, participants were asked to recall all the locations of red squares in the order presented by sequentially clicking the squares on the response screen. Feedbacks including the number of squares that were correctly recalled, the number of errors regarding symmetrical pictures, and the cumulative accuracy of the picture task were presented.

Participants were required to keep at least 85% accuracy on each distracting task. There were 10 trials in the OSpan, and 8 trials in both the RotSpan and SymSpan. Each task lasted about 10 minutes. The whole section of working memory span tasks lasted about 30 minutes.

The all-or-nothing load (ANL) scoring[64] was calculated as the ratio between the sum of the correctly recalled elements in correct serial order and the total amount of elements to be recalled in the task, which is ranged between 0 and 1. The ANL is the mostly used method to evaluate the performance in the OSpan, RotSpan, and

	Mean	SD	Min	Max
Intellectual ability				
FSIQ	97.01	8.07	79	117
VCI	99.05	9.49	80	125
PRI	93.13	10.29	73	121
WMI	98.78	9.76	77	122
PSI	100.81	11.48	81	135
Cognitive control				
CCC (bps)	3.82	0.62	2.04	5.08
EC (ms)	−144.06	41.65	−82.32	−276.42
Working Memory				
Spatial 0-back	0.99	0.02	0.92	1.00
1-back	0.76	0.19	0.17	1.00
2-back	0.51	0.22	0.06	0.99
N-back (2backminus 0back)	−0.47	0.21	−0.92	−0.01
Verbal 0-back	0.95	0.05	0.83	1.00
1-back	0.91	0.11	0.47	1.00
2-back	0.90	0.13	0.38	1.00
3-back	0.87	0.12	0.47	1.00
N-back (3backminus 0back)	−0.09	0.13	−0.53	0.17
OSpan	0.56	0.23	0	1
RotSpan	0.44	0.23	0	1
SymSpan	0.45	0.26	0	1

Table 1. Mean, standard deviation (SD), and range for the indices of behavioral tasks and composite scores of the WAIS-IV. *Note: CCC*: capacity of cognitive control; *bps*: bits per second; *EC*: executive control; *OSpan*: operational span task; *RotSpan*: rotation span task; *SymSpan*: symmetric span task. *FSIQ*: Full Scale Intelligence Quotient; *VCI*: Verbal Comprehension Index; *PRI*: Perceptual Reasoning Index; *WMI*: Working Memory Index; *PSI*: Processing Speed Index.

SymSpan tasks. "All-or-nothing" refers to trials in which all the memory elements were recalled in the correct serial order to be counted as a correct trial, while "load" refers to the response accuracies being weighted by the set size of the memory elements in each trial. Therefore, a higher ANL score indicates a larger working memory span.

Procedure. All the behavioral tasks were compiled and run on a PC using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Participants were required to finish the entire battery of tasks on two separate days within one week. In the first part (day) of the study, each participant first completed three working memory span tasks sequentially: OSpan, RotSpan, and SymSpan. In each span task, they practiced for three trials transitioning from easy to difficult to familiarize with the task, and then continued with the experimental session. After the span tasks, they completed 10 subtests of the WAIS-IV, in a fixed order. Each subtest took approximately 6–8 minutes to complete, for a total duration of approximately 60–80 minutes. In the second part (day) of the study, participants completed the MFT-M, ANT-R, spatial N-back task, and verbal N-back task in a fixed order. For each task, a short practice session was performed before the experimental session. Participants were allowed to rest as long as needed between tasks.

Data analysis. To examine the relationship among all the measures, one-tailed Pearson's correlation analyses were conducted. In addition, the Bayes Factor (BF) was calculated for each correlation[65]. A BF greater than 100 indicates decisive evidence for the alternative hypothesis (H_1) that there is a real correlation in the population, a BF greater than 3 suggests substantial evidence for the correlation, while a BF less than 1/3 indicates substantial evidence for the null hypothesis H_0 that there is no correlation in the population, and any BF value ranging from 1/3 and 3 suggests insensitivity of the data to distinguish between the H_0 and H_1[66].

SEM was conducted to estimate the relationship among all the latent variables, using AMOS 18.0[67,68]. A latent variable "cognitive control" (CC) was derived from CCC and EC. A latent variable, "N-back", was derived from the performance indices of two N-back tasks (spatial and verbal), and the other latent variable, "working memory span" (WMS), was derived from three span scores of OSpan, RotSpan, and SymSpan. A second-order latent variable, "working memory" (WM), was derived from the latent variables of N-back and WMS. A latent variable, "Gf", was derived from PRI, WMI, and PSI, and a latent variable "Gc" was derived from VCI. A second-order latent variable, "IQ", was derived from the latent variables of Gf and Gc to represent the general intellectual ability. We used the maximum likelihood estimation method, which is the most commonly utilized, to select the set of values that maximizes the likelihood of observed covariance[69].

	FSIQ	VCI	PRI	WMI	PSI	CCC	EC	Spatial N-back	Verbal N-back	OSpan	RotSpan
VCI	0.68***	—									
	(>100)										
PRI	0.77***	0.31**	—								
	(>100)	(6.20)									
WMI	0.54***	0.28**	0.18*	—							
	(>100)	(2.72)	(0.34)								
PSI	0.55***	0.05	0.33***	0.10	—						
	(>100)	(0.09)	(11.37)	(0.13)							
CCC	0.39***	0.17	0.28**	0.46***	0.16	—					
	(94.25)	(0.29)	(2.72)	(>100)	(0.25)						
EC	0.30**	0.27**	0.21*	0.12	0.14	0.22*	—				
	(4.66)	(2.11)	(0.57)	(0.16)	(0.20)	(0.69)					
Spatial N-back	0.33***	0.21*	0.19*	0.28**	0.20*	0.32***	0.13	—			
	(11.37)	(0.57)	(0.40)	(2.72)	(0.48)	(8.35)	(0.17)				
Verbal N-back	0.16	0.10	0.14	0.15	0.02	0.10	0.06	0.04	—		
	(0.25)	(0.13)	(0.20)	(0.22)	(0.09)	(0.13)	(0.10)	(0.09)			
OSpan	0.30**	0.13	0.18*	0.43***	0.11	0.36***	0.18*	0.15	0.01	—	
	(4.66)	(0.17)	(0.34)	(>100)	(0.14)	(30.92)	(0.34)	(0.22)	(0.08)		
RotSpan	0.32***	0.11	0.27**	0.27**	0.19*	0.17	0.23*	0.12	0.11	0.41***	—
	(8.35)	(0.14)	(2.11)	(2.11)	(0.40)	(0.29)	(0.85)	(0.16)	(0.14)	(>100)	
SymSpan	0.54***	0.33***	0.49***	0.25**	0.28**	0.36***	0.35***	0.21*	0.10	0.34***	0.46***
	(>100)	(11.37)	(>100)	(1.31)	(2.72)	(30.92)	(21.89)	(0.57)	(0.13)	(15.68)	(>100)

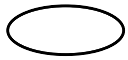
Table 2. Pearson's correlation coefficients (and Bayes Factor values) among all IQ, CC, and WM measures. *Note*: $n = 88$. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$ (one-tailed). Values below the correlation coefficients represent the corresponding Bayes factor (BF). BF > 100: decisive evidence for the correlation; BF > 3: substantial evidence for the correlation; BF < 1/3: substantial evidence for no correlation; $1/3 \le BF \le 3$: insensitivity in detecting correlation.

Model	χ^2 (df)	RMSEA	TLI	CFI	BIC
IQ, CC, and WM	35.33 (39)	0.00	1.04	1.00	156.22
Gc, Gf, and CC	8.12 (7)	0.00	1.02	1.00	70.80
Gc, Gf, and WM	24.09 (25)	0.04	0.95	0.98	113.66
CC and WM	13.83 (13)	0.03	0.98	0.99	80.99

Table 3. Fit indices for all models. *Note: RMSEA*: root mean square error of approximation; *TLI*: Tucker Lewis index; *CFI*: comparative fit index; *BIC*: Bayesian information criterion.

In order to examine the relationship among intelligence, cognitive control, and working memory, we estimated four models: (1) an overall model with IQ, CC, and WM as the latent variables was estimated to examine the relationship among them; (2) a model with Gc, Gf, and CC as latent variables was estimated to directly examine their relationship, and to examine the relationship among different components of IQ (Gc and Gf) and CC; (3) a model with Gc, Gf, and WM as latent variables was estimated to directly examine their relationship, and to further examine the relationship among different components of IQ and WM; and (4) a model with CC and WM as latent variables was estimated to test the relationship between them. Standardized estimates are presented in all models. Negative error variances were constrained to 0[70,71]. Fisher's r-to-z transformation was conducted to test the significance of the difference between two correlations coefficients.

Multiple fit measures, including the ratio of chi-square over degrees of freedom (χ^2/df), root mean square error of approximation (RMSEA), Tucker Lewis index (TLI), comparative fit index (CFI), and Bayesian information criterion (BIC), were calculated to assess how effectively the models captured the covariance between the variables. In line with previous publications[72,73], the cut-off criteria used to establish the good fit between the hypothesized model and the observed data were considered acceptable when the χ^2/df is less than 2, the RMSEA is less than 0.06, and the TLI and CFI are above 0.95. If a pair of variables theoretically correlated to each other and showed a modification indices for the covariance between their error variances greater than 4, the error variances in the model were linked to improve the model fit[74,75]. For the model comparison, chi-square difference was tested. In addition, a BIC difference greater than 2 indicates positive evidence against the model with higher BIC (2–6: positive; 6–10: strong; >10: very strong)[76].



Results

The composite scores of the WAIS-IV and the performance scores of the behavioral tasks are shown in Table 1. The mean (and SD) FSIQ score, an estimate of general intellectual ability, was 97.01 (8.07). The mean (and SD) of VCI, PRI, WMI, and PSI were 99.05 (9.49), 93.13 (10.29), 98.78 (9.76) and 100.81 (11.48), respectively. The mean (and SD) of the CCC and the EC were 3.82 (0.62) bps and −144.06 (41.65) ms, respectively. The mean (and SD) performance indices of the spatial and verbal N-back tasks were −0.47 (0.21) and −0.09 (0.13), respectively. In addition, the mean (and SD) of ANL scores was 0.56 (0.23) for OSpan, 0.44 (0.23) for RotSpan, and 0.45 (0.26) for SymSpan.

Correlation among the composite scores of the WAIS-IV and all task performance. Correlation coefficients between the composite scores of the WAIS-IV, different measures of cognitive control and working memory, and BF values are shown in Table 2. For the correlation coefficients among the measures within each construct, the FSIQ was significantly and positively correlated to all its composite scores (VCI, PRI, WMI, and PSI) in the WAIS-IV ($rs = 0.54$–0.77, $ps < 0.001$). VCI was significantly correlated to PRI ($r = 0.31$, $p = 0.002$) and to WMI ($r = 0.28$, $p = 0.004$), while PRI was significantly correlated to WMI ($r = 0.18$, $p = 0.045$). WMI was not correlated to PSI ($r = 0.10$, $p = 0.171$, BF < 1/3). The CCC was significantly and positively correlated to EC ($r = 0.22$, $p = 0.021$), indicating that higher CCC was associated with more efficient EC (less negative conflict effect). The spatial N-back was significantly correlated to the SymSpan only ($r = 0.21$, $p = 0.027$), the verbal N-back was not correlated to any other WM measures ($rs = 0.01$–0.10, $ps > 0.05$, BF < 1/3), and the three WM complex spans were significantly and positively correlated to each other ($rs = 0.34$–0.41, $ps < 0.001$).

For the correlation coefficients between measures of different constructs, we report coefficients that are only relevant to our hypothesis testing. Refer to Table 2 for all the other coefficients. The FSIQ was significantly correlated to CCC, EC, spatial N-back, OSpan, RotSpan, and SymSpan ($rs = 0.30$–0.54, $ps < 0.01$); the VCI was significantly correlated to EC, spatial N-back, and SymSpan ($rs = 0.21$–0.33, $ps < 0.05$); the PRI was significantly correlated to CCC, EC, spatial N-back, OSpan, RotSpan, and SymSpan ($rs = 0.18$–0.49, $ps < 0.05$); the WMI was significantly correlated to CCC, spatial N-back, OSpan, RotSpan, and SymSpan ($rs = 0.25$–0.46, $ps < 0.01$), but not to the EC ($r = 0.12$, $p = 0.274$, BF < 1/3); the PSI was correlated to spatial N-back, RotSpan, and SymSpan ($rs = 0.19$–0.28, $ps < 0.05$), but not correlated to either CCC ($r = 0.16$, $p = 0.069$, BF < 1/3), and EC ($r = 0.14$, $p = 0.095$, BF < 1/3); the CCC was significantly correlated to spatial N-back, OSpan, and SymSpan ($rs = 0.32$–0.36, $ps < 0.001$); the EC was significantly correlated to OSpan, RotSpan, and SymSpan ($rs = 0.18$–0.35, $ps < 0.05$).

Structural equation mod n ural

WM, $z = 7.50$, $p < 0.001$ (one-tailed), suggesting that a greater amount of variance was shared between Gf and WM than between Gc and WM. In addition, Gf and Gc were signi cantly correlated ($r = 0.47$, $p < 0.001$), a result consistent with ndings from a previous study (Friedman *et al*

of cognitive control for the coordination of thoughts and actions between attentional episodes. Even within each attentional episode, cognitive control is necessary to achieve subgoal-directed behavior. Therefore, this strategy of cognitive segmentation is consistent with our information theory account of cognitive control that is to reduce uncertainty[44].

In the current study, we showed the correlation between CCC and IQ in a homogenous group of young participants with mean IQ scores around 100, and standard deviations of maximally 11 IQ points. In another study of our group[123], a significant correlation between CCC and IQ was found ($r = 0.55$, $p = 0.003$) in a group of individuals ($n = 27$) with higher mean IQ scores (mean = 124.56, SD = 12.70), indicating that our model is also valid in neurotypical groups with higher IQ scores. In previous studies on goal neglect[115,119], major performance failures of tests were restricted to participants in the lower range of IQ scores, suggesting that this association is also true in individuals with lower IQ. However, further studies are needed to test the validity of our cognitive control model of human intelligence for neurotypical groups with low Gf. Additionally, our model seems to be able to explain previously shown deficits in the coordination of mental operations in individuals with mental retardation[124,125], neurodevelopmental[126–128], and psychiatric disorders[129–132], resulting from a functional deficit of the areas within the cognitive control network[133].

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Author Contributions

Y.C., T.W. and J.F. designed the experiments; Y.C. and T.K. collected the data; Y.C. analyzed the data. Y.C., A.S. and T.W. equally contributed to the study. All authors discussed the results and contributed to the writing of the paper.

Additional Information

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