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Research Article

Not All Executive Functions Are Related to Intelligence

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ABSTRACT—*Accumulating evidence suggests that executive functions (EFs) are related to intelligence, despite neuropsychological results initially considered evidence of no such relation. However, findings that EFs are not unitary raise the issue of how intelligence relates to different EFs. This study examined the relations of fluid and crystallized intelligence and Wechsler Adult Intelligence Scale IQ to three separable EFs—inhibiting prepotent responses (inhibiting), shifting mental sets (shifting), and updating working memory (updating)—in young adults. Updating was highly correlated with the intelligence measures, but inhibiting and shifting were not. Furthermore, in structural equation models controlling for the inter-EF correlations, updating remained strongly related to intelligence, but the relations of inhibiting and shifting to intelligence were small and not significant. The results indicate that intelligence measures differentially relate to these three EFs, suggesting that current intelligence measures do not equally assess a wide range of executive control abilities likely required for many "intelligent" behaviors.*

Executive functions (EFs) are processes that control and regulate thought and action (e.g., suppressing habitual responses). They are frequently associated with the brain's frontal lobes; individuals with frontal lobe damage, in addition to performing poorly on neuropsychological EF tasks such as the Wisconsin Card Sorting Test, often exhibit deficits in planning, decision making, and generally regulating everyday behavior (Damasio, 1994), which are considered hallmarks of intelligence (e.g., Sternberg, 1988). Despite such deficits, some individuals with frontal lobe damage and corresponding EF deficits show normal intelligence, as measured by traditional psychometric tests such as the Wechsler Adult Intelligence Scale (WAIS), which provides a composite intelligence quotient (IQ) derived from multiple subtests. These paradoxical neuropsychological findings have long been interpreted as evidence that EFs are unrelated to intelligence.

Duncan, Burgess, and Emslie (1995) proposed that this paradox can be resolved by considering Cattell's distinction between fluid intelligence (Gf)—which reflects higher mental abilities, including reasoning—and crystallized intelligence (Gc)—which reflects knowledge acquired, partly through Gf, from culture, education, and other experiences (Carroll, 1993). Because already acquired knowledge may be more robust to frontal damage than fluid reasoning is, frontal lobe patients may show deficits on tests of Gf, but not Gc. Hence, standard intelligence tests like the WAIS may be relatively insensitive to frontal damage because of their partial dependence on Gc measures. Duncan et al. found that frontal patients did show impaired intelligence on measures of Gf, such as Raven's Progressive Matrices Test. Moreover, Duncan, Emslie, Williams, Johnson, and Freer (1996) found that executive problems such as neglecting to carry out goals were related to Gf in both normal adults and frontal lobe patients.

This neuropsychological evidence that Gf may be particularly sensitive to frontal lobe damage has influenced research with normal populations: Many nonneuropsychological studies examining the relation between EFs and intelligence have focused on Gf and largely ignored Gc. However, the distinction between Gf and Gc may be less important for understanding the relations between EFs and intelligence in populations with no frontal degradation. Because knowledge acquisition, the result of which is Gc, may depend partly on Gf (Carroll, 1993), and because there is no brain damage to selectively impair one type of intelligence, Gf and Gc may both be related to EFs in normal young adults. The current study evaluated this hypothesis by examining the relations of EFs to both Gf and Gc.

Previous studies of nonclinical populations have found some evidence that EFs are related to performance on tasks closely

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associated with intelligence (Carpenter, Just, & Shell, 1990; Engle, Tuholski, Laughlin, & Conway, 1999; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Salthouse, Atkinson, & Berish, 2003; Salthouse, Fristoe, McGuthry, & Hambrick, 1998). In addition, Luciano et al. (2001) found that intelligence and working memory capacity, a concept closely related to executive functioning, share common genetic variance. Hence, both neuropsychological and nonclinical studies converge on the conclusion that intelligence is related to EFs.

This conclusion, however, is complicated by emerging evidence that EFs, though correlated, are separable. Miyake et al. (2000) found that three EF latent variables—inhibiting prepotent responses (inhibiting), updating working memory representations (updating), and shifting between tasks or mental sets (shifting)—were moderately correlated but separable in college students. Further, these EFs differentially predicted performance on four complex clinical and cognitive frontal lobe tasks (Wisconsin Card Sorting Test, Tower of Hanoi, random-number generation, and a working memory span test). These results led Miyake et al. to conclude that EFs show both "unity and diversity."

These findings raise the question of how distinguishable EFs relate to intelligence. Given that general intelligence is most closely associated with complex reasoning and problem-solving tasks (Carroll, 1993), and hence is "often taken to concern the highest-level 'executive' or 'supervisory' functions of cognition" (Duncan et al., 1996, p. 258), one might posit that it would relate, possibly equally, to all EFs. However, this possibility remains untested. Although other EFs have been proposed (e.g., time sharing), those examined by Miyake et al. (2000) have largely dominated the literature on the relations among EFs. Available evidence suggests that at least some of these three EFs might be related to intelligence.

Several researchers have argued that intelligence is related to inhibiting. Salthouse et al. (2003) found that inhibiting strongly correlated with Gf in aging adults. Dempster (1991) reviewed a number of findings relating measures of intelligence, such as WAIS IQ and aptitude-test performance, to several types of inhibition in both developmental populations (i.e., populations of children of several ages) and adult populations. These findings led him to state that "intelligence cannot be understood without reference to inhibitory processes" (p. 157).

With respect to updating, Salthouse et al. (2003) found that it correlated with Gf in aging adults. Moreover, numerous researchers examining young adults have found moderate to strong relations between intelligence and working memory capacity (see Ackerman, Beier, & Boyle, 2005). Because working memory tests involve updating to maintain relevant information in the presence of interference, the finding that intelligence is related to working memory capacity makes it likely that intelligence is related to updating.

As for shifting, evidence is mixed. Some studies have found little relation between shifting tasks and intelligence in normal adults (e.g., Rockstroh & Schweizer, 2001). However, Salthouse et al. (1998) found a high correlation between shifting and Gf in aging adults. Dempster (1991) referred to a study finding a small but weak correlation in normal adults between WAIS IQ and the Wisconsin Card Sorting Test, which taps shifting (Miyake et al., 2000). In a study of adolescents, Ardila, Pineda, and Rosselli (2000) also found that performance on the Wisconsin Card Sorting Test correlated with WAIS IQ.

Unfortunately, much of the data on how intelligence relates to different EFs comes from studies using popular neuropsychological tests as EF measures. Such complex EF-frontal tasks are problematic EF measures for several reasons (Miyake et al., 2000). First, they often have poor reliability. Second, because they require controlling lower-level processes, they necessarily contain a good deal of variance unrelated to the EF of interest (i.e., task impurity). Finally, the particular EFs they tap are often unclear.

In this study, we used multiple measures to construct EF latent variables. Because latent variables extract the common variance from multiple measures, task-specific variance and measurement error are largely eliminated, resulting in relatively pure EF measures and increased statistical power. Moreover, the measures we used were simpler EF tasks (taken from Miyake et al., 2000) that are more tractable and well analyzed in the literature, making their cognitive requirements better understood than those of complex neuropsychological tasks. Such theoretically based cognitive constructs are an important tool in advancing understanding of intelligence, a still poorly understood psychometric construct (Kyllonen, 1996).

In addition to the issue of how closely individual EFs relate to intelligence, a second question important to understanding the relations between EFs and intelligence has not been answered: Do separable EFs show differential relations to intelligence, as they do to various frontal lobe and complex cognitive tasks (Miyake et al., 2000)? Although there have been some proposals that all EF (and non-EF) abilities should be strongly associated with general intelligence in normal adults (Rabbitt, Lowe, & Shilling, 2001), we know of no study systematically targeting the issue of how closely each of several EFs is related to intelligence and whether these relations are differential. Hence, we examined the relations of several intelligence measures (Gf, Gc, and WAIS IQ) to inhibiting, updating, and shifting.

METHOD

Participants

Participants were 234 twins from the Colorado Longitudinal Twin Study. They were representative of the general population in their cognitive abilities (e.g., they showed a normally distributed WAIS IQ distribution; see Table 1). All human research guidelines were followed, and anonymity and confidentiality were maintained. The model estimation procedures corrected for the nonindependence of the twin pairs.

TABLE 1
Descriptive Statistics

									Twin correlation	
Task	*N*	Mean	*SD*	Minimum	Maximum	Skewness	Kurtosis	Reliability	MZ	DZ
Antisaccade	230	.83	.11	.45	.99	−0.91	0.50	.90[b]	.62*	.03
Stop-signal	220	280 ms	60	151	503	1.06	1.49	.80[b]	.62*	.09
Stroop	221	222 ms	81	52	469	0.52	0.04	.80[b]	.47*	.18
Keep-track	231	.79	.10	.44	1.00	−0.73	1.09	.65[c]	.47*	.30*
Letter-memory	232	.86	.10	.53	1.00	−0.71	0.31	.51[c]	.57*	.01
Spatial 2-back[a]	232	1.17	0.19	0.50	1.57	−1.20	1.86	.91[c]	.29*	.08
Number-letter	230	361 ms	200	−23	985	0.85	0.58	.76[b]	.51*	.16
Color-shape	224	317 ms	186	−82	974	0.90	1.12	.97[b]	.48*	.19
Category-switch	230	360 ms	196	–83	998	0.71	0.15	.78[b]	.53*	.18
Raven	232	21	4	12	29	−0.06	−0.65	.84[d]	.56*	.37*
Block Design (WAIS)	234	11	3	4	19	0.13	0.19	.88[e]	.60*	.43*
Vocabulary	231	26	10	1	61	0.66	0.67	.76[b]	.89*	.55*
Information (WAIS)	234	11	3	5	19	0.26	–0.08	.89[e]	.77*	.63*
WAIS IQ	234	103	11	73	142	0.41	0.63	.97[e]	.84*	.41*

Note. MZ = monozygotic (identical); DZ = dizygotic (fraternal); WAIS = Wechsler Adult Intelligence Scale.
[a]Scores for this task were arcsine transformed because of a ceiling effect. [b]Internal reliability was calculated by adjusting split-half correlations (Part 1–Part 2 for the vocabulary task and odd-even for all others) with the Spearman-Brown prophecy formula. [c]Reliability was calculated using Cronbach's alpha. [d]Internal reliability from DeFries, Plomin, Vandenberg, and Kuse (1981). [e]Internal reliability from Wechsler (1997).
*$p < .05$.

Materials, Design, and Procedure

The majority of the EF tasks were taken from Miyake et al. (2000), with some of the tasks from that study modified or replaced to make them more appropriate for the general population or improve their validity, their reliability, or both. Participants completed the EF tasks (computerized) at ages 16 to 18 ($M = 17$, $SD = 0.27$) and the intelligence measures (paper and pencil) at ages 16 to 17 ($M = 16$, $SD = 0.27$).

Inhibiting

The inhibiting tasks required suppressing dominant or automatic responses. In the antisaccade task (Roberts, Hager, & Heron, 1994), participants suppressed the reflexive tendency to look at a cue and instead looked in the opposite direction to identify a briefly appearing target (dependent variable, or DV = proportion correct). The stop-signal task (Logan, 1994) allowed participants to build a prepotent word-categorization response, then asked them to withhold that response on trials with beeps (DV = estimated stop-signal reaction time; see Logan). In the Stroop task (after Stroop, 1935), participants resisted the dominant tendency to read color words, instead naming the incongruent font color; on neutral trials, participants named the color of a string of asterisks (DV = naming time on incongruent trials – naming time on neutral trials).

Updating

The updating tasks required adding and deleting information in working memory (all DVs = proportion correct). In each trial of the keep-track task (after Yntema, 1963), participants saw a set of two to four target categories and a series of 15 words, then recalled the last word presented that belonged to each of the target categories. In each trial of the letter-memory task (after Morris & Jones, 1990), participants continuously said the last three letters presented in a running series of unpredictable length (five, seven, or nine letters), then recalled the final three letters presented once the series stopped. In the spatial 2-back task, participants saw a screen with small boxes darkened in a random order and indicated whether each darkened box was the same as the one darkened two trials before.

Shifting

The shifting tasks required participants to switch between subtasks (DV = reaction time on switch trials − reaction time on no-switch trials). On each trial, a random cue indicating which subtask to perform was presented just before the stimulus and remained on the screen until the participant responded. In the number-letter task (Rogers & Monsell, 1995), participants switched between classifying numbers and classifying letters. In the color-shape task (Miyake, Emerson, Padilla, & Ahn, 2004), participants switched between classifying shapes and classifying colors. In the category-switch task (Mayr & Kliegl, 2000), participants switched between classifying the animacy of words and classifying the size of words.

Intelligence

Gf was measured with two tasks tapping problem-solving and reasoning abilities. In Raven's Progressive Matrices Test (Raven, 1960), participants chose which pieces completed complex

TABLE 2
Correlation Matrix

Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Antisaccade	—													
2. Stop-signal	.43*	—												
3. Stroop	.24*	.22*	—											
4. Keep-track	.21*	.23*	.20*	—										
5. Letter-memory	.32*	.25*	.25*	.42*	—									
6. Spatial 2-back	.17*	.19*	.10	.28*	.29*	—								
7. Number-letter	.23*	.28*	.24*	.21*	.22*	.13*	—							
8. Color-shape	.20*	.34*	.27*	.20*	.17*	.15*	.47*	—						
9. Category-switch	.26*	.30*	.20*	.13*	.13*	.16*	.48*	.52*	—					
10. Raven	.23*	.03	.03	.33*	.24*	.28*	.07	.00	.09	—				
11. Block Design (WAIS)	.19*	.05	.12	.26*	.22*	.17*	.01	.06	.11	.43*	—			
12. Vocabulary	.12	.16*	.16*	.51*	.32*	.15*	.11	.25*	.26*	.29*	.36*	—		
13. Information (WAIS)	.17*	.19*	.10	.41*	.24*	.15*	.04	.15*	.16*	.38*	.37*	.68*	—	
14. WAIS IQ	.25*	.21*	.19*	.52*	.37*	.25*	.06	.16*	.23*	.47*	.62*	.69*	.80*	—

Note. The correlation matrix was estimated with maximum likelihood and was adjusted for nonindependence and missing data by Mplus. For reaction time measures, scores were reversed so that higher numbers indicate better (faster) performance. WAIS = Wechsler Adult Intelligence Scale.
***$p < .05$ for $N = 234$.**

patterns. In the WAIS Block Design subtest (Wechsler, 1997), participants used blocks to reconstruct patterns. This subtest has been used previously to measure Gf because of its sensitivity to frontal damage (Lezak, 1995) and close relation to other Gf tasks (Carpenter et al., 1990). Gc was measured with two tests assessing acquired knowledge. A multiple-choice vocabulary test (described in DeFries, Plomin, Vandenberg, & Kuse, 1981) required participants to identify the synonyms or definitions of words. The WAIS Information subtest asked questions tapping general factual knowledge. WAIS IQ, a composite general intelligence measure based on 11 subtests, was also examined. Except for WAIS IQ, the DV for each measure of intelligence was the number correct.

Statistical Procedures

We used Mplus 3.1 (Muthén & Muthén, 2004) to estimate latent variable models with missing data (34 participants were missing data for one or more tasks because of experimenter, equipment, or participant error; see Table 1). Because the participants were twin pairs, we used an Mplus option that calculates parameters, standard errors, and a scaled chi-square robust to nonindependence. Because models with sample sizes necessary for latent variable analyses often show a significant chi-square (suggesting poor fit to the data) despite only trivial differences between the model's predictions and the observed data, we used the common criterion of the chi-square divided by the degrees of freedom being less than 2 as an indication of adequate fit. We also used two other fit criteria recommended by Hu and Bentler (1998): Bentler's comparative fit index (CFI) greater than .95 and standardized root mean squared residual (SRMR) less than .08. Significance of correlation and path coefficients was ascertained by testing whether dropping them resulted in a significant chi-square difference, appropriately scaled (Satorra & Bentler, 2001); this method is more reliable than test statistics based on standard errors (Gonzalez & Griffin, 2001).

RESULTS AND DISCUSSION

Descriptive information and zero-order correlations for the individual tasks are presented in Tables 1 and 2.[1] To examine the relations between the EFs and intelligence, we used confirmatory factor analysis (CFA), a procedure that allows one to extract latent variables based on a priori factor patterns and estimate the correlations between these latent variables. Specific hypotheses can be evaluated by imposing model constraints (e.g., constraining a correlation to zero) and testing whether the constrained model provides a significantly worse fit to the data (indicated by a significant χ^2 difference test). We estimated a CFA with the three EFs, Gf, and Gc. The top portion of Table 3 provides the factor loadings of each task on its latent variable, and the bottom portion provides the interfactor correlations. The tasks all loaded significantly on their intended constructs, and model fit was good, $\chi^2(55) = 84.10, p = .007$; $\chi^2/df = 1.53$; $CFI = .952$; $SRMR = .044$.

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[1] Table 1 presents raw twin correlations based on approximately 60 monozygotic and 50 dizygotic twin pairs. Although this sample is too small to provide accurate estimates of heritabilities, the generally higher correlations for monozygotic twins (who share 100% of their genes) than for dizygotic twins (who share on average 50% of their genes) suggest that the abilities tapped by these tasks, and likely the latent variables, are heritable. Note that the lower intertwin correlations for dizygotic twins do not mean that dizygotic individuals had lower intertask correlations than monozygotic individuals, so the correlations between measures pooled over zygosity (Table 2) are not driven by the monozygotic data.

TABLE 3

Confirmatory Factor Analysis with Gf and Gc

Variable	Latent factor Inhibiting	 Updating	 Shifting	 Gf	 Gc
	Factor loadings				
Antisaccade	.61*				
Stop-signal	.64*				
Stroop	.43*				
Keep-track		.72*			
Letter-memory		.60*			
Spatial 2-back		.41*			
Number-letter			.65*		
Color-shape			.73*		
Category-switch			.72*		
Raven				.67*	
Block Design (WAIS)				.65*	
Vocabulary					.86*
Information (WAIS)					.79*
	Interfactor correlations				
Inhibiting	—				
Updating	.62*	—			
Shifting	.64*	.39*	—		
Gf	.29	.64*	.13	—	
Gc	.31*	.68*	.31*	.62*	—

Note. For reaction time measures, scores were reversed so that higher numbers indicate better (faster) performance. Gf = fluid intelligence; Gc = crystallized intelligence; WAIS = Wechsler Adult Intelligence Scale.
$^*p < .05$.

Before examining the correlations of the EFs with Gf and Gc, we wanted to determine whether the structure of EFs found by Miyake et al. (2000) with a selected sample (college students) was replicated in this sample, which was more cognitively representative of the general population. Miyake et al. found that inhibiting, shifting, and updating were moderately correlated (*r*s = .42 to .63) but separable (none of the correlations could be set to 1.0 without harming model fit). As shown in the top three rows of the correlation matrix in Table 3, the EF correlations ranged from .39 to .64, all within the 95% confidence intervals of the respective correlations found by Miyake et al. Model comparisons including only the EFs, to make the analyses comparable to those of Miyake et al., indicated that constraining any EF correlation to one or zero worsened model fit (all *p*s < .001). Hence, these data replicate the unity and diversity of EFs found by Miyake et al.

Turning now to the EF-intelligence correlations, shown in the last two rows of the correlation matrix in Table 3, Gf showed nonsignificant correlations with inhibiting (.29), $p = .081$, and shifting (.13), $p = .277$, but a larger correlation with updating (.64), $p < .001$. Constraining these correlations to be equal worsened fit, $\chi^2_{\text{diff}}(2) = 17.41, p < .001$. The EF-Gc correlations were slightly higher and all significant, but updating still showed a higher correlation (.68), $p < .001$, than inhibiting (.31), $p = .002$, and shifting (.31), $p < .001$. Constraining these correlations to be equal worsened fit, $\chi^2_{\text{diff}}(2) = 13.42, p < .001$. Hence, the three EFs differentially relate to both Gf and Gc.

The CFA model calculates the EF-intelligence relations without controlling for EF intercorrelations. We used structural equation models (SEMs) to examine how the three EFs relate to intelligence, considering their intercorrelations. SEMs allow for examination of more complex hypotheses by specifying direct paths (i.e., structural relations) from predictors to predicted latent variables in place of correlations. Further, SEMs allow one to estimate how much variance in each predicted variable is explained by the predictors considered together. In the models here, the difference between CFA models and SEMs is analogous to that between correlations and multiple regressions. We estimated an SEM with the correlated EFs predicting Gf and Gc (see Fig. 1; the tasks used to construct the latent variables are not included for simplicity; task loadings remained the same as those in Table 3). Note that the arrow directionality is not meant to imply causality; it merely allowed a test of how the EFs relate to intelligence, controlling for their intercorrelations.[2] Model fit was good, $\chi^2(55) = 84.10, p = .007; \chi^2/df = 1.53$; *CFI* = .952; *SRMR* = .044.[3] Controlling for the other EFs, updating still predicted Gf and Gc, both *p*s < .001, but inhibiting (*p*s = .680 and .145, respectively) and shifting (*p*s = .632 and .295, respectively) did not. Hence, model fit was unharmed when all paths from inhibiting and shifting were dropped, $\chi^2_{\text{diff}}(4) = 4.18, p = .382$, and the resulting path coefficients for updating predicting Gf and Gc were .61 and .67, respectively. As with the CFA, constraining the three EF path coefficients to either Gf or Gc to be equal significantly reduced fit, $\chi^2_{\text{diff}}(2) = 18.91, p < .001$, and $\chi^2_{\text{diff}}(2) = 17.53, p < .001$, respectively. Hence, the SEM results support the CFA finding that the three EFs differentially relate to both Gf and Gc.

In the CFA model, Gf and Gc correlated significantly (.62), $p < .001$, as expected in this sample of normal young adults. In the SEM, when the variance due to the three EFs was removed from Gf and Gc (the resulting residual variances are depicted in the small circles on the far right of Fig. 1), the correlation between them dropped to .17 (still significant, $p = .002$). This decrease was significant; constraining the .62 correlation in the CFA model to .17 significantly reduced model fit, $\chi^2_{\text{diff}}(1) = 13.98, p < .001$. Hence, the EFs, particularly updating, contribute substantially to the Gf-Gc correlation.

We used similar models to examine WAIS IQ, a frequently used composite measure of general intelligence that includes subtests tapping Gf and Gc (two of which were used to construct the Gf and Gc latent variables), as well as other abilities such as short-term memory. Model fits were good, $\chi^2(30) = 37.37, p =$

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[2] Note that the moderate EF intercorrelations resulted in some multicollinearity, which tends to increase the standard errors (decreasing the precision) of the path coefficient estimates.

[3] The CFA and SEM fit indices were identical because these models are "equivalent" in that they mathematically predict the same covariances, but with different theoretical decompositions of these covariances.

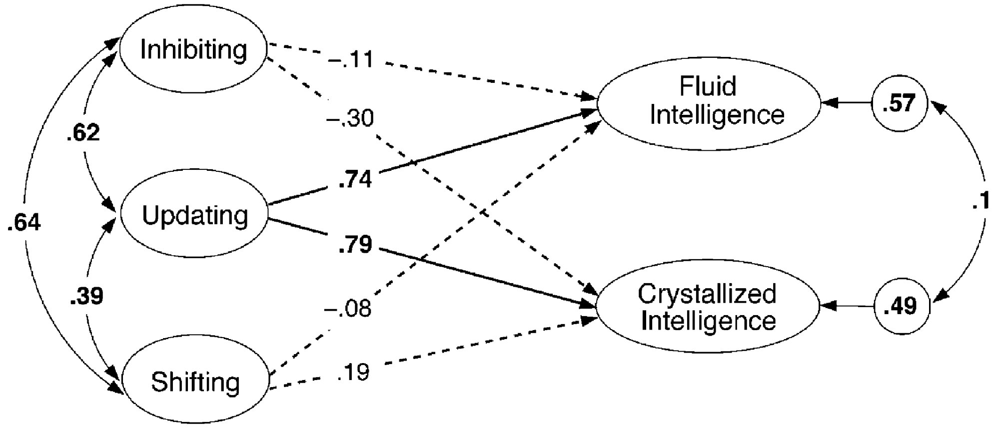

Fig. 1. Structural equation model predicting fluid intelligence (Gf) and crystallized intelligence (Gc) with the three executive functions (EFs). Ellipses represent latent variables. The model is conceptually similar to multiple regressions with Gf and Gc as the dependent variables and the three EFs as correlated independent variables. The numbers on the straight, single-headed arrows are the standardized path coefficients (interpretable as standardized regression coefficients). These numbers reflect the contribution of each EF to Gf and Gc, controlling for the other EFs. Boldface type and solid lines indicate coefficients significant at the .05 level, whereas dotted lines and normal type indicate nonsignificant coefficients. The circled numbers next to the small arrows pointing to Gf and Gc are their residual variances. Subtracting each of these numbers from 1.0 provides the amount of variance in each type of intelligence that is predicted by the three EFs, considered together. Squaring each path coefficient provides the amount of variance in each type of intelligence that is predicted by each EF. The number on the curved arrow connecting the Gf and Gc residual variances indicates the extent to which the two types of intelligence correlate after the variance due to the EFs is removed from each one.

.167; $\chi^2/df = 1.25$; $CFI = .981$; $SRMR = .036$. In the CFA, WAIS IQ significantly correlated with inhibiting (.38), $p < .001$; updating (.69), $p < .001$; and shifting (.23), $p = .003$. These correlations could not be equated, $\chi^2_{\text{diff}}(2) = 33.44, p < .001$. In the SEM predicting WAIS IQ with the correlated EFs,[4] the paths from inhibiting (−.07), $p = .639$, and shifting (−.01), $p = .841$, were not significant, whereas the path from updating (.74), $p < .001$, was. Dropping the paths from inhibiting and shifting did not harm model fit, $\chi^2_{\text{diff}}(2) = 0.54, p = .763$, and the path coefficient from updating alone was .67. As with the CFA, equating the paths between the EFs and WAIS IQ worsened fit, $\chi^2_{\text{diff}}(2) = 42.76, p < .001$. Hence, the EFs showed the same differential relations to WAIS IQ as to Gf and Gc, with updating relating similarly to all three intelligence measures.

GENERAL DISCUSSION

The goal of this study was to examine, in normal young adults, to what extent inhibiting, updating, and shifting relate to intelligence measures, and whether these relations are differential. The conclusions based on Gf, Gc, and WAIS IQ were identical: These three EFs differentially relate to intelligence in normal young adults, with updating being the EF most closely related to intelligence. In the CFAs, the three intelligence measures shared 41% to 48% of their variances with updating, but only 2% to 14% of their variances with inhibiting and shifting. SEMs revealed that when inter-EF correlations were considered, the relations between updating and intelligence measures were undiminished, but the relations between inhibiting and intelligence and between shifting and intelligence were no longer significant. These results suggest that the small correlations of inhibiting and shifting with intelligence measures in the CFAs were due to the variance they shared with updating. Even controlling for its correlations with the other EFs, updating alone accounted for 37% to 45% of the intelligence measures' variances. Moreover, from the CFA to the SEM with Gf and Gc, the Gf-Gc correlation dropped 73%, indicating that the EFs, particularly updating, accounted for a significant portion (though not all) of the Gf-Gc correlation. Note that 49% to 57% of the variances in the intelligence measures were unexplained by the EFs, reflecting the fact that EFs, though important correlates of intelligence, are not the only ones.

In this population of young adults, the three different measures of intelligence showed virtually identical patterns of relationships with the three EFs examined. Although the literature on the relations between EFs and intelligence has focused largely on Gf, the similarity of the results with Gf to the results with Gc and WAIS IQ suggests that Gf may not necessarily be more strongly associated with EFs than are other measures of intelligence in young adults, for whom Gf likely strongly influences knowledge acquisition (the result of which is Gc). However, in populations with reduced frontal integrity, such as older adults and frontal lobe patients, one might expect Gf to show more EF involvement than Gc or WAIS IQ, because Gc may be relatively unaffected by frontally related EF dysfunction (Duncan et al., 1995).

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[4] The three EFs together explained 52% of WAIS IQ variance.

The strong relation between updating and intelligence is consistent with numerous findings of an association between intelligence and working memory capacity (e.g., Carpenter et al., 1990; Engle et al., 1999). These results highlight the importance of updating abilities in current conceptions of intelligence. Updating and working memory capacity have been described as abilities that involve attentional control to maintain relevant information (including task goals) in the face of interference, delete this information when it becomes irrelevant, and replace it with new information (Engle et al., 1999; Miyake et al., 2000). This description overlaps considerably with a definition of intelligence articulated by Binet: "[It] consists of two chief processes: First to perceive the external world, and then to reinstate the perceptions in memory, to rework them, and to think about them" (translation by Carroll, 1993, p. 35).

The weak to nonexistent relations between intelligence and the other two EFs, particularly inhibiting, may initially seem surprising; however, much of the evidence for strong relations between these EFs and intelligence comes from studies of populations with compromised frontal lobe integrity, such as clinical and aging populations (e.g., Salthouse et al., 1998, 2003). Although the current data do not speak directly to the relations between EFs and intelligence in these populations, one possibility suggested by Rabbitt et al. (2001) is that when frontal lobe functioning is generally compromised, multiple EFs may be affected, leading to higher inter-EF correlations. These higher correlations could then result in generally higher EF-intelligence correlations. Indeed, Salthouse et al. (2003), examining an aging sample, found substantially higher inhibiting-updating (.71), inhibiting-Gf (.73), and updating-Gf correlations (.93) than those found here.

The current study has interesting implications for intelligence research. Specifically, the weak to nonexistent relations between the intelligence measures and both inhibiting and shifting highlights some discrepancies between psychometric intelligence measures and many theoretical conceptions of intelligence. Although intelligence theorists have repeatedly noted the importance of inhibiting and shifting abilities to intelligent behavior, tests traditionally used to assess intelligence in normal adults do not seem to tap these two EFs much (if at all).

For example, Thurstone (1924) defined intelligence as self-control over reflexive or instinctive impulses, arguing that inhibiting such impulses allows one to rationally consider options and intelligently adjust to situations. More recently, Sternberg (1988) defined intelligence as "mental self-management" (p. 72) needed to adapt, select, and shape the environment, citing lack of impulse control as one cause of self-management failures. In addition, Dempster (1991) and Das (2002) have argued that the ability to resist interference from distracting, irrelevant information (an ability closely related to inhibiting, as demonstrated by Friedman & Miyake, 2004) is an important component of intelligent behavior. Similar theoretical claims can also be found for shifting, although different terms (e.g., mental or cognitive flexibility) are often used to denote the ability to flexibly switch mental sets or avoid being stuck on ineffective strategies or mundane viewpoints (e.g., Lohman, 2000; Sternberg, 1988). Thus, to the extent that the simple EFs in the current study actually tap these hypothesized roles (see Friedman & Miyake, 2004, for evidence suggesting a link between inhibiting and everyday cognitive functioning), the current finding that not all EFs are related to psychometric intelligence suggests that traditional measures of intelligence are missing some fundamental supervisory functions.

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