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Working Memory and Parent-Rated Components of Attention in Middle Childhood: A Behavioral Genetic Study

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Abstract

The purpose of the current study was to investigate potential genetic and environmental correlations between working memory and three behavioral aspects of the attention network (i.e., executive, alerting, and orienting) using a twin design. Data were from 90 monozygotic (39% male) and 112 same-sex dizygotic (41% male) twins. Individual differences in working memory performance (digit span) and parent-rated measures of executive, alerting, and orienting attention included modest to moderate genetic variance, modest shared environmental variance, and modest to moderate nonshared environmental variance. As hypothesized, working memory performance was correlated with executive and alerting attention, but not orienting attention. The correlation between working memory, executive attention, and alerting attention was completely accounted for by overlapping genetic covariance, suggesting a common genetic mechanism or mechanisms underlying the links between working memory and certain parent-rated indicators of attentive behavior.

Keywords

Behavioral genetics; Working memory; Parent-rated attention; Middle childhood; Twins

Introduction

Children's cognitive regulation involves working memory and several aspects of attention. Better cognitive regulation has been linked with greater academic achievement (Bramlett et al. 2000; Ponitz et al. 2009; Smith et al. 2008) and better social-emotional adjustment

(Barkley 1997; Buckner et al. 2009; Eisenberg et al. 1997). Individual differences in working memory and some but not all components of attention are intricately linked, but the genetic etiology of these links is not well understood. The aim of the current study was to investigate potential genetic and environmental correlations that might explain the covariation between working memory and three aspects of attentive behavior in middle childhood: executive, alerting, and orienting attention.

Working memory and attention

Working memory is the set of mental processes holding limited information in a temporarily accessible state in service of cognition (Cowan et al. 2005). The construct of working memory was first proposed by Baddeley to replace the unitary short-term memory system (Baddeley and Hitch 1974). Attention, as a component in working memory, works as a central executive, and it is responsible for maintaining goals and overriding existing activities in order to achieve longer-term aims. Specifically, this includes two functions: focusing on one stream of relevant information and inhibiting the influence of other streams of information and switching focus when necessary. These two aspects of attention are crucial to successful utilization of working memory when mental manipulation and storage of information both are needed (Baddeley and Sala 1996).

Consistent with this view is empirical evidence showing that people with better attention control have higher working memory capacity, which holds true for all domains of working memory (i.e., verbal as well as visual/spatial working memory; Engle and Kane 2004; Kane et al. 2001; Turner and Engle 1989). When the effortful attention capacity is taxed, performance in working memory tasks in all domains degrades substantially (Engle and Kane 2004). Neurological bases of working memory have indicated a role of the dorsolateral prefrontal cortex (DLPFC) that appears to mediate the executive process of working memory and controlled-attention, (Baddeley 2003; Kane and Engle 2002). These results implicate an anatomical association between controlled attention and executive working memory.

Working memory is often measured with cognitive tasks in different modalities, such as verbal modality (e.g., digit span tasks and word recall tasks) and visual-spatial modality (e.g., picture memory and spatial tracking tasks). Verbal modality is the most often used because it is the best understood among the sub-systems of working memory (Baddeley and Hitch 1994). Therefore, in the current study, we used the verbal forward and backward digit span task from the Stanford-Binet (Thorndike et al. 1986) to measure working memory. Given the verbal expressive component of performance on this task, we also measured and statistically controlled for oral vocabulary using that scale from the Stanford-Binet.

Components of attention—When considering the links between working memory and attention, one must consider that attention is itself a multi-faceted construct. Different aspects of attention may have different relations with working memory. One view of attention, based on behavioral as well as neuroimaging evidence of dissociation between different attention subsystems, is that there are three independent attention subsystems within the attention network: the executive attention, the alerting attention, and the orienting attention (Posner and Petersen 1990). The orienting subsystem is developed very early in infancy (Johnson et al. 1991), and is mainly involved in automatic processing, determining the initial orientation to sensory events. The alerting and executive subsystems develop later in life, and are involved in effortful processing, when sustained vigilance and inhibition of inappropriate responses are required (Posner and Rothbart 2006).

Thus, alerting and executive attention, but not orienting attention, should correspond with the function of a central executive in a working memory system. Developmental behavioral

evidence supports this view. In one study, individual differences in working memory were associated with parent-rated alerting and executive, but not orienting, attention scores among four and a half year olds (Wolfe and Bell 2004). Also, neuroimaging studies of adults have indicated differential activation in DLPFC and anterior cingulate cortex (ACC) as well as differential performance in executive attention and alerting attention tasks in individuals high vs. low in working memory performance (Osaka et al. 2003, 2004, 2007). Based on the literature, our first hypothesis was that working memory would be positively correlated with executive attention and alerting attention, but would not be correlated with orienting attention.

The attention network can be measured using the Attention Network Test (i.e. ANT) which applies difference scores between different cue and flanker conditions to assess the ability to resolve conflict, the ability to initiate and maintain attention, and the ability to disengage (Fan et al. 2002), although the utility of the test for children has only recently been demonstrated (Posner and Rothbart 2006). Fortunately, the three components of attention can also be reliably measured using parents' reports on the Children's Behavior Questionnaire-Short Form or CBQ-SF (Putnam and Rothbart 2006). Executive attention can be measured using the inhibitory control scale, defined as the capacity to plan and to suppress inappropriate approach responses under instructions or in novel or uncertain situations (Rothbart et al. 2001). Alerting attention can be measured using the attention focusing scale, defined as the ability to maintain or sustain attention or remain "on task" (Rothbart et al. 2001). Orienting attention can be measured using the perceptual sensitivity scale, defined as the child's threshold for detecting low intensity stimuli from the external environment (Posner and Raichle 1994). Although the questionnaire-based measure of these three components of attention lack the specificity of the ANT task performance measure, using a task for digit span and reliable parents' ratings for attention has the advantage of reducing the likelihood of inflation of effect sizes due to shared method effects.

Genes and environments

Behavioral genetics provides a method for investigating the etiology of the links between working memory and specific aspects of attention—in particular, whether underlying common genetic or non-genetic influences account for these links. In the current study, we answer this question in a twin study of school-age children. To our knowledge, the current study would be the first to examine this question with respect to working memory and executive, alerting, and orienting attention in childhood; typically, these are studied independently in behavioral genetic research. The prior quantitative genetic studies have shown moderate levels of heritable and nonshared environmental variance for working memory task performance (Ando et al. 2001; Finkel and McGue 1993; Pedersen et al. 1992) and a similar pattern for various measures of attention focusing and control in childhood and adulthood (Deater-Deckard et al. 2006; Fan et al. 2001; Neuman et al. 1999; Sherman et al. 1997). Although findings are mixed, molecular genetic studies have pointed to candidate genes involving Catechol-O-methyltransferase (COMT) for working memory (Egan et al. 2001) and dopamine neurotransmitter genes (e.g., DRD4, DAT1) for attention (Faraone et al. 2001; Li et al. 2006).

Based on this literature, our second hypothesis was that working memory and every aspect of attention would include moderate levels of heritable and nonshared environmental variance, and that shared environmental variance would be negligible. Furthermore, and as the novel thrust of the current study, our third hypothesis was that there would be significant genetic covariance between working memory, executive attention (i.e., measured as inhibitory control), and alerting attention (i.e., measured as attention focusing). In contrast, we did not anticipate finding genetic covariance between working memory and orienting

attention (i.e., measured as perceptual sensitivity), even if there was a significant phenotypic correlation.

Method

Participants

The data were from the second annual wave of the Western Reserve Reading Project (WRRP, a longitudinal twin study). Families were mainly recruited from the Cleveland, Columbus, and Cincinnati metropolitan areas. The average age in the second wave was 7.15 (SD = .67, range = 6.00–8.83). Ninety-two percent of the sample was Caucasian and 5% was African American. There was a wide range of parental educational levels: 12–17% high school or less, 23–27% some college, 31% bachelor's degree, and 25% some post-graduate education or degree. There were 90 pairs of MZ twins (39% male) and 112 pairs of same-sex DZ twins (41% male) that had complete data on all study variables.

Procedure

In the second annual assessment wave, data were collected during a three-hour home visit. Before the assessments, informed consent was obtained and parents were informed that they would receive \$100 for their participation. During the visits, parents and twins completed a series of tests including both behavioral and cognitive assessments. Parents were invited to complete the temperament questionnaire following the second annual home visit by mail.

Measures

Attention—Attention was measured using parents' reports on the Children's Behavior Questionnaire Short Form or CBQ-SF (Putnam and Rothbart 2006). Mothers completed ratings for every participating child; about 50% also had fathers' reports. The CBQ is rated on a 7-point Likert scale (1 = extremely untrue of your child; 4 = neither true nor false of your child; 7 = extremely true of your child). The CBQ assesses fifteen dimensions, among which we focused on the inhibitory control, attention focusing and perceptual sensitivity scales in the current study. Each scale includes 6 items. For twin1, Cronbach's alphas were 0.63 for inhibitory control, 0.64 for attention focusing, and 0.72 for perceptual sensitivity. For twin2, the corresponding alphas were 0.70, 0.76, and 0.79, respectively. Mother-father agreement was moderate (Mullineaux et al. 2009); when available, mother and father ratings were averaged to yield more reliable scores.

Working memory and verbal ability—To assess children's working memory and verbal ability, children completed a shortened version of the Stanford-Binet Intelligence Scale IV (SBIV; Thorndike et al. 1986). SBIV is a standardized test that measures intelligence and cognitive abilities in children and adults. The digit span task, including forward and backward digit span, was used to measure children's working memory. One-year test-retest reliability for digit span task was .62 for twin1 and .57 for twin2. The oral vocabulary task was used to measure children's verbal ability. One-year test-retest reliability for oral vocabulary task was .47 for twin1 and .36 for twin2.

Data analysis

A common-factor independent-pathway multivariate model was applied to examine the genetic and nongenetic variances in and covariances between working memory, inhibitory control, attention focusing, and perceptual sensitivity. In this model, the observed phenotypic variance and covariance were decomposed into latent genetic, shared environmental and nonshared environmental variance and covariance (Fig. 1). Specifically, the variance of and covariance between variables were decomposed into additive genetic

(A), shared environmental (C), and nonshared environmental variance (E) shared by all variables, as well as residual genetic (a_i), shared environmental (c_i), and nonshared environmental variance (including error; e_i) unique to each variable. Due to the fact that monozygotic (MZ) twins share 100% of their genes and dizygotic (DZ) twins share 50% of their genes on average, the correlation for additive genetic similarity between twin 1 and twin 2 was set as 1 and .5 for MZ and DZ twins, respectively. The correlation for shared environment (i.e. environmental factors that lead to twin similarity) between twin 1 and twin 2 was set as 1 for both MZ and DZ twins. The correlation for nonshared environment (i.e., environmental factors that do not lead to twin similarity) between twin 1 and twin 2 was set as 0 for both MZ and DZ twins. This model was fit to twin variance/covariance matrices using maximum likelihood model-fitting procedures in Mx (Neal 1997). Root Means Square Error of Approximation (RMSEA; Steiger 1990), Akaike's Information Criterion (AIC; Burnham and Anderson 1992), and χ^2 test were used to test for model fitting. A RMSEA value below .05, a negative AIC value, and a nonsignificant χ^2 test indicate a close fit. A RMSEA value between .05 and .10 indicates an adequate fit, and a value above .10 indicates a poor fit.

Results

Previous studies have indicated potential sibling contrast effects on parent ratings of child behaviors (Saudino et al. 2000). Therefore, we first examined twin difference scores on the parent rated attention scales and identified 7 outlying pairs (all DZ twin pairs) with extreme difference scores (>3.5 SD difference). These 7 sibling pairs were excluded from the following analyses.

Descriptive statistics of the age standard scores for working memory and the three attention scales are shown in Table 1. Scores were widely distributed, with only modest skewness ($-.40$ to $.38$) and kurtosis ($-.26$ to $.78$). The potential mean level differences in study variables across child sex (0 = female, 1 = male), age, and zygosity (1 = MZ, 2 = DZ) were tested together for twin1 and twin2. Significance tests were adjusted, as suggested by Griffin and Gonzalez (1995), to take into account twin non-independence. For child sex, mean level difference was found for inhibitory control, attention focusing, and perceptual sensitivity ($t = -6.80$ to -3.11 , $p < .01$), suggesting higher inhibitory control, attention focusing, and perceptual sensitivity scores for girls. No mean level difference was found for working memory across child sexes ($t = -1.29$). For child age, attention focusing were significantly correlated with child age ($r = -.18$, $p < .01$), suggesting higher attention focusing scores in younger children. There were no significant correlations between child age and any of the other study variables ($r = -.05$ to $-.04$). None of the study variables showed significant mean level differences across zygosity ($t = -1.37$ to -1.28).

Because working memory and oral vocabulary scores were significantly correlated ($r = .20$, $p < .001$), we regressed digit span on oral vocabulary scores and the standardized residual working memory score was used in subsequent analyses.

Hypothesis 1: phenotypic correlations

The first hypothesis was that working memory would be correlated with executive attention (measured as inhibitory control) and alerting attention (measured as attention focusing), but not with orienting attention (measured as perceptual sensitivity). We estimated bivariate Pearson correlations between study variables together for twin1 and twin2. Significance tests were adjusted to take into account twin non-independence (Table 1; Griffin and Gonzalez 1995). Correlations between the three attention scores were modest to moderate ($r = .28$ to $.60$). Consistent with Hypothesis 1, working memory was positively correlated with attention focusing ($r = .22$) and inhibitory control ($r = .12$), but not with perceptual

sensitivity ($r = .02$). Fisher r -to- z test was used to test for statistically significant differences across correlations. The correlation with working memory for attention focusing and inhibitory control were not significantly different ($z = 1.43, p = .08$). The correlation with working memory for perceptual sensitivity and inhibitory control was not significantly different ($z = 1.40, p = .08$). The correlation between working memory and perceptual sensitivity was significantly different from the correlation for attention focusing ($z = 2.83, p = .00$).

Hypothesis 2 and 3: genetic and nongenetic variance and covariance patterns

Twin intra-class correlations for the study variables were estimated (Table 2). Correlations between MZ twin scores were all higher than DZ twins, suggesting that there was genetic variance in all five variables.

In order to estimate the genetic and nongenetic variance of and covariance between study variables, a multivariate common-factor independent-pathway model (Fig. 1) was applied. Nested models were also tested by fixing certain paths at 0, and χ^2 difference test were used to select the best fitting model among all the competing models to balance the loss in fit with the difference in degrees of freedom. The full model and the best fitting model are presented in Table 3. Compared to the full model (RMSEA = .036; AIC = -42.03), the trimmed model had a great improvement in fit (RMSEA = .006; AIC = -57.11; $\Delta\chi^2 = .91, \Delta df = 8, p > .05$). Therefore, results from the best fitting model were interpreted. It is important to note that two non-significant paths were retained in the best fitting model: unique genetic (a) and unique shared environmental (c) path to working memory. This was because the resulting pattern of model comparisons suggested that it was not possible to distinguish between specific a and c for working memory. The model with only unique genetic path fixed at 0 ($\chi^2 = 55.03, df = 57, p = .55$; RMSEA = .000; AIC = -58.97) had virtually equivalent fit to the model with only unique shared environmental path fixed at 0 ($\chi^2 = 56.18, df = 57, p = .51$; RMSEA = .009; AIC = -57.82). In addition, the model with both paths fixed at 0 at the same time ($\chi^2 = 62.45, df = 58, p = .32$; RMSEA = .026; AIC = -53.55) fit significantly worse than the models with only one path fixed at 0, and the model with both paths retained. Given the equivocal nature of these results, both paths were retained in the final model because it was not possible to distinguish them.

Univariate genetic variance was calculated by summing the squared shared and unique genetic path estimates (i.e., $h_{univ}^2 = A^2 + a^2$). Genetic variance in working memory, inhibitory control, attention focusing, and perceptual sensitivity was .21, .55, .32, and .27, respectively. Shared environmental and nonshared environmental variance was calculated in the same way (i.e., $C_{univ}^2 = C^2 + c^2$; $E_{univ}^2 = E^2 + e^2$). Shared environmental variance in working memory, inhibitory control, attention focusing, and perceptual sensitivity was .21, .17, .10, and .48, respectively. Nonshared environmental variance for the four variables was .58, .29, .57, and .25, respectively.

Multivariate results from the best fitting model suggested that there was a general genetic factor underlying working memory, attention focusing, and inhibitory control, represented by significant path estimates from A (.35, .37, and .57). This general genetic factor was not shared by perceptual sensitivity, represented by a negligible path from A to perceptual sensitivity. All genetic variance in perceptual sensitivity was unique (a: .52). After controlling for the general genetic variance, there was remaining unique genetic variance for working memory (a: .30) and inhibitory control (a: .64), but not for attention focusing. Significant overlapping shared environmental variance was found across inhibitory control, attention focusing, and perceptual sensitivity, represented by significant path estimates from C (.41, .32, and .69). This general shared environmental factor was not shared by working

memory; instead, all shared environmental variance in working memory was unique ($c: .46$). There was also significant overlapping nonshared environmental variance across the three components of attention ($E: .54, .45$, and $.11$), but not working memory. All nonshared environmental variance in working memory was unique ($e: .76$).

Discussion

Attention and memory are two of the most heavily investigated aspects of cognitive function and self-regulation in the history of psychology (Ebbinghaus 1964; James 1890), but the rising interest in the developmental and biological etiology of the connection between them and other aspects of self-regulation is relatively recent (Bell and Deater-Deckard 2007). Evidence from behavioral and neurological studies (mostly of adults) has indicated potential common mechanisms that are shared by working memory and some but not all aspects of attention (Engle and Kane 2004; Osaka et al. 2007). The aim of the current study was to advance the literature by testing several hypotheses regarding genetic and environmental influences on the links between working memory and three aspects of attention (executive, alerting, and orienting) in childhood.

Hypothesis 1: phenotypic correlations

The first hypothesis was that at the phenotypic level, working memory would be positively correlated with both executive attention (measured as parent-rated inhibitory control) and alerting attention (measured as parent-rated attention focusing), but would not be correlated with orienting attention (measured as parent-rated perceptual sensitivity). The results supported this hypothesis. Significant positive correlations were found between inhibitory control and working memory ($r = .12$) and attention focusing and working memory ($r = .22$), but not between perceptual sensitivity and working memory ($r = .02$). The phenotypic correlations above were unlikely to reflect any effects of child age. Two of the three attention scores measured by the CBQ were not correlated with child age, and the working memory and oral vocabulary scores were age standardized scores. One previous study of younger children found similar results, but with slightly larger effect sizes (Wolfe and Bell 2004). One potential explanation for the smaller phenotypic effect sizes in the current study compared to this prior study is our use of a digit span task as the sole working memory measure—an important caveat that we return to below.

Thus, by the time children begin school, it is possible to identify the hypothesized links between working memory and the two most effortful aspects of attention (executive and alerting), and to also see that working memory is independent of the more automatic and non-effortful orienting attention—using simple measures of memory and attentive behavior. This is consistent with the adult literature on the links between effortful attention and working memory, in verbal as well as visual/spatial domains (Engle and Kane 2004; Kane et al. 2001; Turner and Engle 1989). The phenotypic evidence may reflect underlying maturation of the neural networks involved in attention and memory regulation that involve DLPFC and ACC—regions of the brain that are involved in effortful attention and working memory (Baddeley 2003; Kane and Engle 2002; Posner and Rothbart 2006). A somewhat distinct “adjustable attention” view is that working memory depends on the scope of attention, in regard to the number of items that can be stored in working memory at a time—though more recent research suggests attentional scope and control, though neurologically distinct, are not separable as part of a coordinated effortful or executive attention system (Cowan et al. 2005). Accordingly, attention functions like a camera by focusing to hold on to a task goal in the face of interference, and zooming out to apprehend other items if the need arises. Those who have better attentional control have larger attentional scope and will more likely execute working memory effectively when it is needed. This integrated system may be detectable by the time children are old enough to begin school.

In contrast, individual differences in automatic or non-effortful orienting attention reflect influences that are correlated with the effortful aspects of attention (correlations were in the .3 range in the current study), but that nevertheless are independent of working memory. Of the three aspects of the attention network, brain activity locations associated with degree of orienting attention (measured as perceptual sensitivity in the current study) are the more posterior and farthest away from the more anterior regions associated with working memory, when compared to the effortful alerting and executive components of attention (Posner and Rothbart 2006). Developmentally, it is only in childhood that the perceptual sensitivity dimension is correlated with inhibitory control and attention focusing. By adulthood and perhaps by some point in adolescence, perceptual sensitivity becomes independent of the effortful components of attention; it no longer loads on the higher-order effortful control factor in Rothbart's theory and measures of temperament (Evan and Rothbart 2007; Putnam et al. 2001). The lack of a phenotypic correlation between working memory and orienting attention (i.e., perceptual sensitivity) in the current study also rules out overlapping genetic influence between working memory and this particular aspect of the attention network.

Hypotheses 2 and 3: genetic and nongenetic influences

Our second and third hypotheses addressed questions about the etiology of the variance in, and covariance between, working memory and these three aspects of attention in childhood. The second hypothesis was that there would be moderate heritable and nonshared environmental variance (but little shared environmental variance) in all of the study variables. Univariate results suggested a slight deviance from this hypothesis: modest to moderate genetic variance (.21 to .55), modest shared environmental variance (.10 to .48), and modest to moderate nonshared environmental variance (.25 to .58) was found for all study variables. The detection of shared environmental variance is unexpected based on results from previous univariate studies (e.g., Fan et al. 2001). One plausible explanation to this distinct result is that multivariate analyses in the current study provide us the power to detect the shared environmental variance that is associated with method effect, a point we return to below.

The multivariate behavioral genetic analyses allowed us to test the third hypothesis: that there would be an underlying genetic covariance between working memory, inhibitory control (our measure of executive attention), and attention focusing (our measure of alerting attention). We also tested for potential shared and nonshared environmental covariances (see Fig. 1; Table 3). The results were consistent with the theory that working memory and certain aspects of attention are partially the same construct (Baddeley and Hitch 1974). According to that theory, effortful attention (i.e. executive attention and maintenance of alerting state) is an essential part of working memory, responsible for keeping an active state of central information and monitoring potential interference, be it verbal or spatial. However, from a behavioral genetic perspective, working memory and components of effortful attention are not merely the same construct. There was unique genetic variance in working memory that did not overlap with genetic variance in alerting attention and executive attention. The non-genetic variance in working memory was also independent from that in alerting and executive attention.

The most parsimonious interpretation is that there is a common set of genetic factors that accounts for the covariation between effortful aspects of the attention network and working memory in middle childhood. Note that this result was not attributable to expressive verbal ability (measured as oral vocabulary). That variance was removed from the verbalized digit span task score. Furthermore, in supplementary behavioral genetic analyses not reported above, there was no evidence of a genetic correlation between verbal ability and any aspect of attention. Therefore, it is highly unlikely that the results are due to genetic influences on underlying verbal ability.

In addition, all the covariation between the effortful aspects of the attention network and working memory was mediated through this common set of genetic factors. As can be seen from the results, there is no non-genetic covariance between working memory and the effortful aspects of the attention network. Given that prior quantitative genetic studies have suggested negligible shared environmental variance in working memory and various aspects of attention (Ando et al. 2001; Deater-Deckard et al. 2006; Fan et al. 2001; Finkel and McGue 1993; Pedersen et al. 1992; Sherman et al. 1997), the current shared environmental variance and covariance found using a multivariate decomposition is very likely a representation of method effect (e.g., situational factors and parent rating bias). The pattern of multivariate results is consistent with this argument. First, the shared environmental variance for working memory is independent from the overlapping shared environmental variance across the three attention constructs. This may be due to the fact that we used a task measure for working memory and parents' ratings for the three aspects of the attention network. In addition, after controlling for the common shared environmental variance, there is no unique shared environmental variance remaining for any of the attention construct, indicating the likelihood of a shared method effect. Hence, the unique design of the current study (i.e., using a task measure for working memory and parent ratings for different aspects of attention) not only minimizes the potentially inflated effect sizes attributable to shared method covariance in previous studies, but also highlights the biological etiology of the link between working memory and effortful aspects of attention. The current results indicate that the anatomical integration of working memory and effortful aspects of attention has its genetic origins.

The unique genetic influences that are specific to working memory and executive attention might be age-specific, and as a result, may change across the lifespan. Among all cognitive abilities, executive abilities such as working memory and executive attention undergo the longest periods of development before reaching maturation (Kostovic et al. 1988). During this prolonged development, the brain undergoes a great deal of change and rearrangement of connections between cortexes (Diamond 2002). By late adolescence or young adulthood, the underlying genetic mechanisms and neural connections linking working memory and the effortful aspects of the attention network may be different from during childhood. Consistent with this notion is evidence of strong developmental increases in genetic variance for attention (Deater-Deckard and Wang, in press) and cognitive abilities more generally (McCartney et al. 1990; Plomin et al. 1997). Furthermore, the phenotypic correlation between working memory and effortful aspects of attention may also increase from childhood to adulthood (r s in .15 to .35 range in school-age children vs. r s in .35 to .45 range in adults; Osaka et al. 2007; Redick and Engle 2006; Wolfe and Bell 2004). These studies, although not sufficient on their own, provide preliminary support for the idea that the overlapping genetic influences on working memory and the effortful aspects of attention increase in magnitude, reflecting increasing integration of the memory and attention components of a broader executive function system.

Caveats and conclusions

The current study examined the genetic and environmental links between working memory and different aspects of the attention network. However, there are some limitations in the measures. In regard to working memory, it is feasible to ask school-age children to do backward as well as forward span tasks (Marcovitch et al. 2010), but backward span tasks are certainly very difficult for young children. Average performance does not reach adult-like levels until about 13 years of age (Diamond 2002). Given our sample of 6–9 year olds, some of the children may have been too young to fully understand the backward task. However, even if this is true, forward and backward span performance was significantly correlated (.35), lending some credence to the validity of the more difficult backward span

task. This correlation is not much lower than the .5 correlation between backward and forward span performance in adults (Gregoire and Van der Linden 1997). Regarding measurement of attention, the parent ratings are not task-based measures of cognitive functions involved in attention (Posner and Rothbart 2006). Having questionnaire-based measures of aspects of attention might have influenced effect sizes in the study. However, parent ratings can be valid and reliable behavioral measures of these attention components (Davis et al. 2001; Posner and Raichle 1994; Rothbart et al. 2001; Rueda et al. 2005). Furthermore, advantages of using parents' reports for attention and task performance for working memory is that we were able to minimize shared method covariance that could inflate effect size and more importantly, that could emerge as common shared environmental variance across working memory and different aspects of the attention network which would potentially obscure the nature of the link between them.

Another limitation is that behavioral genetic methods do not identify which genes are implicated. Of course, that is an exciting ongoing effort in current molecular genetics research that ultimately will answer these questions regarding which specific sets of genes are responsible for linking different aspects of cognitive self-regulation together. It is our goal to eventually map these variances and covariances onto the structural variations in DNA that account for the variances and covariances. To this end, dopamine neurotransmitter genes would be good candidates. Variation in dopamine receptor 4 gene (DRD4) has been associated with attention behaviors across many studies (Faraone et al. 2001; Li et al. 2006), and may also help explain the developmental increase in heritable variance in the transition to middle childhood and beyond (Deater-Deckard and Wang, in press). In regard to the serotonin neurotransmitter system, studies have established the important role that it plays in self-regulation processes (Canli et al. 2005; Krakowski 2003; Reuter et al. 2007). In particular, variation in serotonin transporter gene 5-HTT and its synthesis rate-regulating enzyme tryptophan hydroxylase (TPH) gene has been associated with attention regulation.

In conclusion, in middle childhood, working memory, executive attention and attention focusing shared a common source of underlying genetic covariance that accounted for all of the phenotypic associations between them. More behavioral genetic studies are needed to replicate and extend the finding, at different stages of development. Molecular genetic studies are needed to map the associations on measurable structural variations in DNA, and to explain how, through genetic influence, different brain areas and activities are organized to integrate different aspects of cognitive self-regulation. The current study's results would suggest that when they are identified, many of the genetic influences that operate on working memory will also operate on some but not all aspects of the attention network. Furthermore, there will be ample variance arising from non-genetic influences that will explain individual differences in these cognitive self-regulation skills.

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Fig. 1.

Multivariate common-factor independent-pathway model was used to partition the variance of and covariance among working memory, inhibitory control, attention focusing, and perceptual sensitivity into genetic, shared environmental and nonshared environmental components. Latent variables represent overlapping additive genetic (A), shared environmental (C), and nonshared environmental (E) covariance, as well as residual genetic (a1 to a4), shared environmental (c1 to c4), and nonshared environmental (e1 to e4) variance. The correlations between latent genetic variance and covariance across twins were set at 1 for MZ twins and .5 for DZ twins. For both MZ and DZ twins, the correlations for shared environmental and nonshared environmental variance and covariance across twins were set at 1 and 0, respectively

Table 1

Descriptive statistics and correlations

	Inhibitory control (IC)	Attention focusing (AF)	Perceptual sensitivity (PS)	Working memory (WM)
IC	5.07 (.80)			
AF	.60 ***	5.01 (.90)		
PS	.34 ***	.28 ***	5.39 (.79)	
WM	.12 *	.22 ***	.02	52.51 (5.17)

Numbers on-diagonal are means (standard deviations) of the study variables. Numbers off-diagonal are correlations between study variables

$N = 195$ pairs

*
 $p < .05$.

**
 $p < .01$.

 $p < .001$

Table 2

Intra-class correlations for MZ and DZ twins

	MZ	DZ
IC	.76***	.36***
AF	.54***	.08
PS	.73***	.62***
WM	.45***	.32***

See Table 1 for variable abbreviations

 $N = 195$ pairs*
 $p < .05$.**
 $p < .01$.***
 $p < .001$

Table 3

Multivariate common-factor independent-pathway model: standardized paths estimates and fit indices

	A	C	E	a	c	e	χ^2 (df, p)	AIC	RMSEA
Full model									
Working memory	.33*	.07	.00	.32	.45	.76*	53.98(48, .26)	-42.03	.036
Inhibitory control	.37*	.41*	.54*	.60*	.21	.00			
Attention focusing	.57*	.34*	.44*	.00	.00	.61*			
Perceptual sensitivity	.00	.69*	.11*	.52*	.00	.49*			
Best fitting model									
Working memory	.35*	-	-	.30	.46	.76*	54.89(56, .52)	-57.11	.006
Inhibitory control	.37*	.41*	.54*	.64*	-	-			
Attention focusing	.57*	.32*	.45*	-	-	.61*			
Perceptual sensitivity	-	.69*	.11*	.52*	-	.49*			

A, C, and E are common genetic, shared environmental, and nonshared environmental pathways; a, c, and e are genetic, shared environmental, and nonshared environmental pathways that are unique to each variable. -, path fixed to 0.

* $p < .05$