ATTENTION DEFICITS AND WORKING MEMORY: PHONOLOGICAL AND VISUOSPATIAL MEMORY SUBSYSTEMS AS MEDIATORS OF CENTRAL EXECUTIVE FUNCTION AND SCHOLASTIC ACHIEVEMENT IN CHILDREN

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ABSTRACT

Baddeley's (1990) empirically based model of attention and working memory provides the necessary framework for investigating the relative influence of phonological and visuospatial working memory as potential mediators of attention deficits and intelligence in affecting scholastic achievement in children. In the present study, we sought to determine the extent to which vigilance (an indicator of central executive function) and intelligence affect early and long-term scholastic achievement in 300 school-aged children after controlling for relevant sociodemographic variables (age, SES) using a cross-sectional, longitudinal design. A mediator model was subsequently examined to determine whether phonological and visuospatial memory subsystems independently attenuate the relationship between intelligence and central executive functioning and children's early and long-term scholastic achievement consistent with hypotheses derived from Baddeley's (1990) model of working memory.

Structural equation modeling (SEM) was used to examine and compare the baseline and mediator models. Collectively, the results support the role of phonological working memory as an important mediating variable between both central executive functioning and early intelligence, and long-term scholastic achievement in children. Implications of these results for understanding the developmental trajectory of children with attention deficits and general theoretical models of Attention-Deficit/Hyperactivity Disorder (ADHD) are discussed.

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CHAPTER 1. INTRODUCTION

The complex relationship among children's intelligence, attentional problems, and scholastic achievement has been widely studied and the subject of multiple reviews (e.g., Hinshaw, 1992). Interest in the tripartite association may be due to several factors. Estimates of learning problems in samples of children with attention deficits range from 18% to 56%, depending on the method by which learning problems and attention deficits are defined (Cantwell & Satterfield, 1978; Frick et al., 1991; Holborrow & Berry, 1986; Lambert & Sandoval, 1980). Children with attention deficits receive more failing grades and fail more grades than comparison children (Barkley, Fischer, Edelbrock, & Smallish, 1990; Faraone et al., 1993; Minde, Weiss, & Mendelson, 1972; Weiss, Hetchman, Perlman, Hopkins, & Werner, 1979). An estimated 25% (Mannuzza, Kline, Bessler, Malloy, & Hynes, 1997) to 31% (Weiss, Hetchman, Milroy, & Perlman, 1985) of children with ADHD fail to complete high school. And, many of the cognitive deficits associated with attentional problems in children are thought to be secondary to general, and more specifically, verbal intelligence (Werry, Elkind, & Reeves, 1987).

Disentangling the interplay among attention deficits, scholastic achievement, and intelligence, and understanding the underlying processes and directional nature of their relationship has become a priority for clinical child researchers. Some have suggested that learning problems, specifically deficits in reading, may precede attention deficits (McGee & Share, 1988). Recent empirical evidence, however, supports the opposite view - namely, that attention deficits precede and contribute to the development of learning problems (Fergusson & Horwood, 1992). Others have speculated that the verbal intelligence deficits commonly seen in children with attention deficits may represent the

essential feature from which most other common cognitive symptoms stem (Werry et al., 1987). This possibility, however, fails to account for the finding that ADHD symptomatology also is related to cognitive deficits in non-verbally mediated domains and remains evident after controlling for intelligence (Cantwell & Satterfield, 1978; Faraone et al., 1993; Frick et al., 1991; Rapport, Scanlan, & Denney, 1999). A third possibility is that children with ADHD experience specific cognitive deficits, over and above their problems with impulsivity and hyperactivity, that interfere with their ability to learn academically related information (Frick et al., 1991). Attentional deficiencies appear to be the strongest candidate, have received the greatest degree of empirical scrutiny, and are highlighted in both categorical (American Psychiatric Association, 1994) and dimensional (Achenbach, 1991) views of the disorder. The contributing role of attentional problems as a core cognitive mechanism also is corroborated by recent findings wherein 89% of 46 between-group studies reviewed found significant vigilance deficiencies in children with ADHD compared with normal controls (Rapport, Chung, Shore, & Isaacs, 2001).

Despite the strong association between attentional problems and learning difficulties, the mechanisms or processes by which difficulties with attention develop into academic problems remain poorly understood. A likely candidate involves the interplay between attention and working memory. Working memory difficulties are well documented in children with ADHD (Benezra & Douglas, 1988; Berman, Douglas, & Barr, 1999; Douglas & Benezra, 1990; Kinsbourne & Caplan, 1979; Voelker, Carter, Sprague, Gdowski, & Lachar, 1989) and serve as important (Barkley, 1997) or central (Denney & Rapport, 2000; Rapport, 2001) elements in theoretical accounts of ADHD. Corroborative

evidence concerning the involvement of working memory as a core process in ADHD stems from recent reviews of objective measures found to differentiate ADHD from non-clinical samples (Rapport et al., 2001) and past findings of significant improvement on tasks requiring working memory following psychostimulant treatment (Dalby, Kinsbourne, & Swanson, 1989; Douglas, Barr, Amin, O'Neill, & Britton, 1988; Rapport, Loo, & Denney, 1995; Rapport, Stoner, DuPaul, Birmingham, & Tucker, 1985).

The interplay among attentional problems, working memory, and long-term scholastic achievement was recently examined in the context of a dual developmental pathway model, wherein children's classroom behavior and cognitive function (attention, working memory) accounted for 77% of the variance in long-term scholastic underachievement (Rapport et al., 1999). Examination of the model also reveals that the vigilance-working memory cognitive pathway is a more robust mediator of ADHD and long-term scholastic achievement than are classroom behavior problems. These findings, coupled with those of recent reviews of clinic and laboratory testing paradigms (Rapport et al., 2001), suggest that vigilance-working memory processes in ADHD merit closer scrutiny.

Bridging the clinical and cognitive sciences may help elucidate the mechanisms by which attention deficits, working memory, and intelligence interact in affecting children's scholastic achievement. For example, Baddeley's (1998) model of working memory illuminates the dynamic interplay between a controlling attentional system (the *central executive*) and subsidiary phonological and visuospatial systems used in learning. Briefly, the attention-controlling central executive is assumed to govern the two subsidiary systems. The phonological subsystem is used to manipulate speech-based information

(e.g., phonological learning, vocabulary acquisition, language comprehension), whereas the visuospatial sketchpad handles and manipulates visual images and visual-spatial learning (e.g., manipulating visual images and carrying out spatial tasks, visual spatial memory, geographical orientation). Extensive empirical evidence exists concerning the separate functions of the two subsystems (Isaacs & Vargha-Khadem, 1989; Logie, 1986; Michas & Henry, 1994; Pickering, Gathercole, & Peaker, 1998; Smith, Jonides, & Koeppe, 1996) and their oversight by the central executive (Baddeley, 1996).

Baddeley's empirically based model of attention and working memory provides the necessary framework for investigating the relative influence of phonological and visuospatial working memory as potential mediators of attention deficits and intelligence in affecting scholastic achievement in children. In the present study, we sought to determine the extent to which vigilance (an indicator of central executive function) and intelligence affect early and long-term scholastic achievement after controlling for relevant sociodemographic variables (i.e., age and SES were included as covariates) using a cross-sectional, longitudinal design. The structure of the baseline model is depicted in Figure B.1.a. A mediator model was subsequently examined to determine whether phonological and visuospatial memory subsystems independently attenuate the relationship between intelligence and central executive functioning and children's early and long-term scholastic achievement consistent with hypotheses derived from Baddeley's (1990) model of working memory. A schematic of the mediator model is depicted in Figure B.1.b. At the most general level, we hypothesized that the central executive contributes to both early and long-term scholastic achievement after controlling for its expected association with intelligence, and that intelligence is associated with both

early and long-term scholastic achievement after controlling for its expected association with central executive functioning (see Figure B.1.a). We also hypothesized that the association between central executive functioning and long-term scholastic achievement would be attenuated if phonological and visuospatial memory systems proved to be important mediators of the relationship (see Figure B.1.b). Visuospatial memory was expected to have a weak or nonsignificant relationship with both early and long-term scholastic achievement in children due to the heavy reliance on phonological mechanisms in most educational settings. Moreover, we expected the pathways between the central executive (vigilance) and the two memory subsystems (phonological, visuospatial) to be nearly equivalent based on extant research indicating that they are both controlled by the central executive and operate independently of one another (Logie, 1986; Pickering et al., 1998). We also considered the magnitude of the regression coefficients linking intelligence (IQ) with early and long-term scholastic achievement, and felt that it would be moderately attenuated if part of IQ's continuity with scholastic achievement is mediated by the two memory systems. Finally, we expected to explain additional variance in scholastic achievement (indicated by a lower disturbance term or unexplained variance in SEM terminology) compared to the baseline model owing to the inclusion of mediating variables.

CHAPTER 2. METHODS

Participants

The sample consisted of 300 children (136 males, 164 females) between 7 and 16 years of age (x = 10.72, SD = 2.42) attending public and private schools in Honolulu (Oahu), Hawaii[1]. Approximately 72% of the State's population resides in the City and County of Honolulu (U.S. Bureau of the Census, 2000). Schools were selected based on available data suggesting that their ethnic and sociodemographic composition was a close approximation of children residing in Hawaii (State of Hawaii Data Book, 1996).

The public school is a research arm associated with the University of Hawaii whose primary mission is to develop and test curricula suitable for children of differing abilities and sociodemographic backgrounds. Children are admitted to the school based on ethnicity, gender, parental socioeconomic and marital status, residence location, and academic achievement to approximate the State's census.

A private school was selected for participation to obtain a sample reflecting the relatively large number of children (i.e., 19%) attending private schools in the State (State of Hawaii Data Book, 1996). The school admits students from throughout the State, although the majority of children reside in the urban Honolulu area.

An informational letter, consent form, and demographic information form were mailed to parents of children attending both schools. The letter provided a basic description of the research project. The latter two forms were used to obtain written consent for children's participation and sociodemographic information (Duncan, 1961) concerning family members, respectively. Parental consent was obtained for 100% and 54% of the children attending the University-affiliated public school (participation in

approved research studies is a required condition of admission) and private school, respectively. The obtained consent rate compares favorably with that reported in other school sample studies (e.g., Kearney, Hopkins, Mauss, & Weisheit, 1983; Severson & Ary, 1983). Subjects were classified by six ethnic categories: East Asian (36%), Part-Hawaiian (23%), Caucasian (11%), Southeast Asian (4%), Pacific Islander (less than 1%), and Mixed (25%). Subjects were labeled as "Part-Hawaiian" if any ethnicities within their ethnic background included Hawaiian. Subjects were labeled as "Mixed" if the ethnicities within their ethnic background could not be categorized by just one of the other ethnic categories.

Child Intelligence

The Kaufman Brief Intelligence Test (K-BIT) consists of two subtests designed to assess domains parallel to crystallized and fluid intelligence as described by Horn and Cattell (1966), and the verbal-performance dichotomy proposed by Wechsler (1981). It yields scores on vocabulary and a matrices task that can be combined to yield a composite IQ. The matrices subtest was used as a manifest variable in the structural equation models to provide an estimate of children's intelligence (note: matrices rather than composite IQ was used owing to the expected redundancy between K-BIT vocabulary and measures of phonological memory). The psychometric properties of the K-BIT and expected patterns of relationships with other measures of intelligence have been well established in past samples (Kaufman & Kaufman, 1990). The matrices subtest, termed "IQ", was used as a manifest variable in constructing the models (x = 111.20; SD = 13.63) and is considered an excellent measure of g or general ability (for a review, see Kaufman & Kaufman, 1990).

Early Scholastic Achievement

The Kaufman Test of Educational Achievement (K-TEA Brief Form) is an individually administered diagnostic battery that measures mathematics, reading, and spelling skills in children. Its psychometric properties and expected patterns of relationships with other measures of educational achievement have been well established in past samples (Sattler, 1989). Subtest scores combine to yield a composite achievement score. A latent variable representing individual differences in achievement corrected for measurement error was derived using the composite score of the K-TEA as an indicator variable (termed "Early SA" [early scholastic achievement] in the model) and fixing its error term based on its published test-retest reliability coefficient (Kaufman & Kaufman, 1998) as recommended by Kline (1998).

Central Executive Functioning

The Continuous Performance Test (CPT) paradigm programmed for use in the present investigation was based on a comprehensive literature review that reflected its prevalent use by researchers as a measure of vigilance and controlled information processing (Coons et al., 1981; Schachar, Logan, Wachsmuth, & Chajczyk, 1988; Sergeant & van der Meere, 1990), and by extension, an indicator of central executive function (Baddeley & Logie, 1999). The low and high target density "BX" or double-letter version of the CPT used in the study requires the child to respond (using the click mechanism of the track ball) on each occasion wherein an identical letter of the alphabet is displayed consecutively (i.e., repetitions of the same letter). Visual stimuli consisting of letters of the alphabet are presented in the center of the monitor screen (3.5 cm high, 3.5 cm wide) at 1-sec intervals (0.2 s display, 0.8 s intertrial stimulus interval) throughout

the 9-min duration of the test. Fifteen or 60 target stimuli (consecutive identical letters) are randomly dispersed throughout each 3-min block of the CPT, with a total of 45 or 180 target stimuli occurring during the 9-min testing session for the low and high target density versions, respectively. Prior to testing, children are required to identify letters of the alphabet to insure letter recognition and participate in 1-min practice sessions until a criterion of 80% correct target identification is met.

A latent variable termed "CEF" (central executive functioning) was derived using percent of correct identifications (hits) of target stimuli for the double-letter CPT paradigm.

Phonological Memory

Paired Associate Learning Tasks (PAL-T) are related to classroom learning (Baddeley, Papagno, & Vallar, 1988; Stevenson, 1972) and used to assess working memory (Carroll, 1993). The task was selected because it places heavy demands on the phonological loop, particularly when the paired associations involve learning arbitrary relationships (for a review, see Baddeley et al., 1988; Douglas & Peters, 1979).

Prior to testing, children are required to identify letters of the alphabet and digits 0 through 9 to ensure letter and number recognition, respectively, prior to participating in a brief practice session. The task requires children to learn arbitrary associations between letter bigrams (e.g., "GJ") and single numerical digits (e.g., "3") in six blocks of five bigram-digit pairs. Bigram-digit stimuli are pre-programmed in a library file and presented on a color monitor. A bigram is presented in the middle of the computer screen with its associate digit below. Children are required to place the arrow on the digit and click the track ball device to ensure orientation and facilitate learning. Following

presentation of five bigram-digit pairs to be learned, a test phase ensues and requires children to correctly identify (using a track ball device) the digit (digits 0 through 9 are shown at the bottom of the screen) that was previously associated with the bigram. Incorrect responses during the test phase are followed by a computer tone and corrective feedback. Bigram-digit pairs are assessed three times in random order during the test phase. Following the test phase, a new block consisting of five bigram-digit associations is presented then tested for recall. This procedure continues until all six blocks of paired associations are presented and assessed for recall.

A latent variable termed "phonological memory" was used in the models and derived by averaging the number of correct responses for the three, two-block combinations (i.e., blocks 1 and 2, 3 and 4, 5 and 6, respectively).

Visual Memory

The Stimulus Equivalence Paradigm (SEP) involves a form of conditional matching of sample stimuli and dissimilar choice stimuli. This instrument was selected because it reflects many of the same paired associate learning processes used in the PAL-T, but the stimuli consist of abstract geometric designs that would be extremely difficult to encode phonologically and require the use of the visual-spatial sketchpad (Baddeley, 2000).

Stimulus equivalence paradigm (SEP) description and procedures. This computer paradigm is a form of matching-to-sample in which children are presented with abstract geometric designs consisting of arbitrary shapes to minimize or eliminate the child's ability to encode the information by means of phonological processing (i.e., the shapes are complex and bare no obvious resemblance to real life shapes or figures that can be named). At the beginning of a trial, three abstract geometric figures (approximately 8 cm

x 12 cm) are presented in a horizontal arrangement across the bottom, middle, or top third of the computer monitor screen (i.e., the screen is divided into 3 equivalent horizontal rows). The center stimulus is boxed (highlighted by a colored line) and the child is required to make an "observing response" to it by placing the cursor anywhere within the box and clicking the response mechanism on the track ball. This ensures attention to the central stimuli and provides a measure of latency to initial response and between responses. Following the observing response, a second row of three, similarly sized, abstract geometric figures appear in one of the remaining two row locations on the screen. Row placement of both sample and response (to-be-matched) stimuli is determined randomly for each trial to eliminate the possibility of learning associations based on location. The child's task is to learn which one of the three response stimuli is associated with the center sample stimulus by means of trial and error learning (i.e., the relationship between stimulus pairs is strictly arbitrary - no association can be made based on shape, size, or location). If the child selects the correct response stimulus, a colored line to indicate a correct match immediately boxes it accompanied by a high-pitched tone. If the child selects an incorrect response stimulus, the computer emits a low-pitched tone and boxes the correct stimulus design to facilitate future learning. The child must then place the cursor anywhere in the correctly boxed stimulus and click on the track ball mechanism before proceeding. The location of the correct response stimulus (i.e., left, center, or right placement in the row) is randomly determined for each trial by a pre-built library file. Following both correct and incorrect responses, the monitor screen becomes blank for a 2-s intertrial interval, followed by the presentation of a new sample stimulus in one of the three row locations as described above. This

procedure continues throughout the acquisition phase of the study (see Acquisition phase, below).

Verbal instructions provided to the children were limited to describing the basic paradigm and procedures described above.

Pretesting. A level setting procedure and practice session is used prior to formal testing. The procedure consists of establishing task difficulty based upon each child's age and K-BIT composite IQ. Its purpose is to minimize floor and ceiling effects by establishing a common level of task difficulty across age and intelligence levels (for details, see Vyse & Rapport, 1989). Level setting procedures permit assignment to one of three levels (i.e., 5, 6, or 7 stimuli per grouping) based on the child's age and IQ. The practice session (approximately 5 minutes) serves to familiarize children with the paradigm and is repeated until a child is able to correctly match three pairs of stimuli.

Stimulus relations. Children learn the stimulus relations, through trial and error, among three groupings (A, B, or C) of stimuli, with each group containing 5, 6, or 7 geometric stimuli based on the level setting procedure. Children learn that each stimulus contained in the A group is associated with a particular stimulus in the B group, and that each stimulus in the B group is associated with a particular stimulus in the C group (e.g., A1 = B1, B1 = C1, A2 = B2, B2 = C2...). Stimuli in the A and C group are never directly paired to permit assessment of higher-order (transitive) learning. Thus, a child working on level 6 will be directly taught 12 stimulus pairings using a total of 18 designs (i.e., six stimuli in each of the three [A, B, C] groupings). A schematic depicting the stimulus equivalence paradigm and stimulus examples is shown in Figure B.2.

Acquisition/review phase. During the acquisition phase, children initially learn the A-to-B relationships (e.g., A1 = B1), then the B-to-C relationships (e.g., B1=C1). Forestalling the presentation of additional sample-choice relations until a child emits two consecutive correct responses ensures the learning of sample-choice relationships for each newly presented pair of stimuli. A review phase is presented immediately after the acquisition phase at which time all previously learned paired stimulus relations (i.e., all A-to-B and B-to-C) are presented twice in random order to minimize the influence of recency and latency effects.

Test phase. Following the completion of the review phase (i.e., after completion of all training) children are instructed that they will play a "bonus game" and to try and correctly match the center and response stimuli as they had done in the previous phase. They are also informed that neither the tone or box will be presented after they select a response stimuli, but that the computer will record their correct choices and to try to answer as many correct as possible (i.e., unreinforced test phase).

The test phase lasts approximately 20 minutes during which time children are presented with five of each directly taught (reflexive learning) stimulus relationships (e.g, A-to-B, B-to-C), five indirectly learned or reverse (symmetric learning) stimulus relationships (e.g., B-to-A, C-to-B), and five higher-order (transitive learning) never before associated stimulus relationships (e.g., A-to-C, C-to-A). Thus, a child working on level 5 would receive a total of 150 test trials (50 trials for each of the three types of learning).

Dependent measures. A latent variable termed "visual memory" was used in the models and derived using the percent of correctly identified pairs of trained, symmetric,

and transitive relationships during the test phase (for specific details, see Vyse & Rapport, 1989).

Long-Term Scholastic Achievement

The Stanford Achievement Test (SAT; 1996) is a national, group-administered test for 3rd to 12th grade children that is used to assess long-term SA across multiple domains and for purposes of college entry. A latent variable termed "long-term SA" was used in the models and derived from total reading, total math, and total language scale scores. Scale scores represent approximately equal units on a continuous scale, using numbers that range from 1 through 999, and are suitable for studying change in performance over time. SAT scores were collected between 3 and 4 years after children were initially tested at the clinic (note: the difference in time frame for collecting SAT data is related to when subsequent testing is conducted by the schools, viz., 3rd, 6th, 9th, 11th, and 12th grades).

Socioeconomic Factors and Age

Socioeconomic status, computed for each child's family using the Duncan Index (Duncan, 1961), and children's age were both partialled out of all variables in the model to control for their potentially confounding effects on modeled relationships. Neither is included in the structural model figures for purposes of conceptual clarity.

Procedures

Each child was seen once per week over a 2-week time period at the Children's Learning Clinic. Children's intelligence (K-BIT), vigilance (CPT), early scholastic achievement (KTEA), phonological memory abilities (PAL-T), and visual memory abilities (SEP) were individually assessed by trained graduate students for approximately 1.5 hrs during each of the two clinic visits. Ordering of testing was counterbalanced

across sessions with the exception of the intelligence test and stimulus equivalence paradigm (SEP). Intelligence assessment always preceded administration of the SEP owing to the level setting procedures associated with the SEP. Breaks (5-min) were scheduled between tests to minimize fatigue. SAT scores were collected from school records between 3 and 4 years after children were initially tested at the clinic

Children were seated such that the computer monitor was approximately 0.5 m from the child with the center of the screen at eye level. An experimenter was present throughout all testing, situated approximately 3 m behind the child during administration of the computerized tasks.

CHAPTER 3. RESULTS

A two-tier approach was used to address the primary purposes of the study. In the first tier, we sought to determine the extent to which central executive functioning and intelligence were related to early and long-term scholastic achievement in children after controlling for relevant sociodemographic variables (i.e., age and SES were included as covariates). A mediator model was subsequently examined to determine whether phonological and visuo-spatial memory subsystems independently attenuate the relationships between intelligence and central executive functioning and children's early and long-term scholastic achievement consistent with hypotheses derived from Baddeley's (1990) model of working memory. Both models were fitted to the covariance matrix of indicator variables shown in Table A.1. (i.e., 9 variables for the Baseline Model [Figure B.1.a.]; all 15 variables for the Mediator Model [Figure B.1.b.]) using Amos 3.61 (Arbuckle, 1997) and maximum-likelihood estimation. Age and SES adjusted scores were used in both models for all variables but omitted from the diagrams for purposes of visual clarity.

Model identification for the Baseline and Mediator Models was achieved by fixing the unstandardized loading of one indicator variable for each of the latent variables in the models. This procedure is followed because latent variables are not directly measured and thus require a measurement scale to calculate estimates of effects that involve them. Fixing the unstandardized loading of one indicator per factor to 1.0 gives the latent variable the same metric as that indicator (i.e., a 1-point increase in the factor is associated with a 1-point increase in the indicator variable). Once the unstandardized loading is fixed, the SEM model is estimated using the total and error variance associated

with the indicator from which its standardized loadings (as shown in the figures) can be determined.

Absolute and incremental fit indices were used to evaluate the extent to which the proposed models accounted for observed relationships among variables. Evaluation of model fit describes the degree of congruence between patterns of relationships implied by a model and those observed among the manifest indicator variables incorporated into it. The selection of specific fit indices was based on extensive review of recommendations published in the structural equation literature (cf., Bentler, 1992; Hoyle, 1995; Kline, 1998; Maruyama, 1998).

Absolute indices

(1) The Goodness of Fit Index (GFI) indicates the proportion of covariances among observed variables accounted for by model-implied covariances (Kline, 1998). Values range from 0 to 1.0. A value of 1.0 indicates perfect fit. Values >.90 are indicative of adequate fit.

(2) The chi-square statistic is overly sensitive to sample size and not recommended as a fit index when sample size is large as in the current study (Hu & Bentler, 1995). An adjusted chi-square is recommended to address this problem and involves dividing the chi-square value by the degrees of freedom (Kline, 1998). A χ^2/df ratio less than 3 is desirable.

(3) The Root Mean Square Error of Approximation (RMSEA; Browne & Cudeck, 1993) represents the average difference between correlations expected on the basis of a model's assumptions and those observed among measured variables. This index includes an adjustment for the number of variables incorporated into

a model so that parsimony is taken into account. Values falling below 0.10 indicate adequate fit (Kline, 1998).

Departure of this index from the desired range can be evaluated for statistical significance (i.e., the magnitude of difference can be evaluated against the range of variation observed under chance conditions).

Incremental indices

(1) The Comparative Fit Index (CFI; Bentler, 1990) indicates the proportional improvement in the overall fit of a theoretical model relative to a null model in which all the observed variables are assumed to be uncorrelated. An obtained CFI value of .98, for example, indicates that the relative overall fit of the model is 98% better than that of the null model estimated with the same sample data.

(2) The Bentler-Bonnett Nonnormed Fit Index (NNFI) is similar to the CFI but includes an adjustment for model complexity. This adjustment favors parsimonious models over less parsimonious ones.

Ideally, high GFI and low χ^2/df and RMSEA values should be observed in conjunction with high CFI and NNFI values. This pattern indicates that a proposed model satisfactorily accounts for observed variances and covariances and that the observed variances and covariances are large enough to be meaningful.

Absolute and incremental fit indices were used to evaluate the strength of fit between the variance/covariance matrix estimated from the model parameters and the variance/covariance matrix calculated from the sample data (see Table A.1.). The regression weights (factor loadings) between each latent variable and its corresponding manifest indicator variables were subsequently examined to evaluate the internal

consistency of the hypothesized latent variables. Path coefficients between the variables in the model were evaluated as a final step to examine the strength of relationships between intelligence, central executive functioning, memory, and scholastic achievement. In keeping with convention, the measurement portion of the model is discussed prior to explication of the structural components (Hoyle & Panter, 1995).

Baseline Model (Figure B.3.)

The measurement portion of the Baseline Model describes the relationship between the three latent constructs (i.e., Central Executive Functioning [CEF], Early Scholastic Achievement [Early SA], and Long-Term Scholastic Achievement [Long-Term SA]) and their respective manifest variables (i.e., Set 1: percent of correct identifications on the BX-Low and BX-High vigilance paradigms; Set 2: the KTEA composite score as a single indicator with its associated fixed error term based on the test-retest reliability of the instrument; Set 3: Stanford Achievement Test Reading, Math, and Language composite scores, respectively). The factor loading of an indicator variable represents its correlation with the construct it is presumed to measure. The psychometric reliability of the indicator is equal to the proportion of its variance explained by the underlying construct. Thus, an indicator's reliability is determined by squaring its factor loading. The proportion of its variance that is unexplained (i.e., unique) is the complement of this value (i.e., 1 minus squared loading). This value can also be obtained by squaring the value labeled "E" in Figure B.3.

The squared loading for reading, math, and language SAT composite scores were .85, .77, .72, respectively, indicating good internal consistency of these measures (see

Figure B.3.). A similar range of factor loadings was found for early scholastic achievement and central executive functioning.

The structural component of the model describes the relationships between the latent variables of the model. The relationships among these variables is presumed to reflect the following causal structure:

a) Central Executive Functioning and IQ are correlated, exogenous (or independent) variables;

b) Central Executive Functioning exerts both direct and indirect effects on Long-Term SA, the latter by means of its influence on Early SA;

c) IQ exerts both direct and indirect effects on Long-Term SA, the latter by means of its influence on Early SA.

Fit indices were calculated initially in our evaluation of the Baseline Model. Absolute (GFI = .97; RMSEA = .07; 90% confidence interval = .04 - .09; χ^2/df = 2.52) and incremental fit indices (CFI = .98; Bentler-Bonnett NNFI = .97) indicate a strong fit between the variance/covariance matrix for the sample data and hypothesized model.

Inspection of the pathways reveals significant relationships between central executive functioning and early (β = .27, p<.05) and long-term scholastic achievement (β = .13, p<.05) after accounting for its shared relationship with intelligence (r = .15, p<.05), and allowance for measurement error in the indicator measures (see Es in Figure B.3.). Intelligence also contributed to early (β = .49, p<.05) and long-term achievement (β = .12, p<.05) after accounting for its shared relationship with central executive functioning (r = .15, p<.05). Finally, early scholastic achievement showed strong continuity with

long-term achievement after accounting for individual differences in IQ and executive functioning ($\beta = .55$, $p<.05$).

Mediator Model (Figure B.4.)

The expanded model tests the plausibility of pathways hypothesized to mediate the relationship between central executive functioning and long-term scholastic achievement. Specifically, it posits that phonological and visuospatial memory subsystems mediate the direct and indirect (via early scholastic achievement) relationship between the central executive and long-term scholastic achievement consistent with hypotheses derived from Baddeley's (1990) model of working memory.

The measurement component of the Mediator Model describes the relationships between 5 sets of indicator variables (Set 1: percent of correct identifications on the BX-Low and BX-High vigilance paradigms; Set 2: percentage of correct responses for three, two-block combinations on the Paired Associate Learning Test; Set 3: percent of correctly identified pairs of trained, symmetric, and transitive relationships on the Stimulus Equivalence Paradigm; Set 4: the KTEA composite score as a single indicator with its associated fixed error term based on the test-retest reliability of the instrument; Set 5: SAT Reading, Math, and Language composite scores) and their respective latent constructs (CEF, Phonological Memory, Visual Memory, Early SA, Long-Term SA). Factor loadings within the measurement component of the Mediator Model ranged between .77 and .98, indicating good internal consistency for each of the latent variables (see Figure B.4.).

The structural component of the Mediator Model describes the linkages between the two independent (CEF, IQ) and four dependent variables (Phonological Memory, Early

SA, Visuospatial Memory, Long-Term SA). The relationships among these variables are presumed to reflect the following causal structure:

a) Central Executive Functioning and IQ are assumed to be correlated, exogenous (independent) variables;

b) Central Executive Functioning (after controlling for its shared effects with IQ) is related to both Phonological and Visuospatial Memory subsystems based on predictions stemming from Baddeley's model (1997) of working memory;

c) Central Executive Functioning is related to Long-Term SA indirectly through mediating relationships with Phonological Memory and Early SA after its correlation with IQ is taken into account. The indirect pathway from CEF to Early and Long-Term SA via Visuospatial Memory, however, is expected to be marginal or non-significant due to the heavy reliance on phonological skills and processing in educational settings;

d) Phonological Memory exerts both direct and indirect effects on Long-Term SA, the latter by means of its initial influence on Early SA;

e) IQ exerts both direct and indirect effects on children's Long-Term SA, the latter by means of its influence on Phonological Memory and Early SA after accounting for its correlation with CEF.

Fit indices were calculated initially in our evaluation of the Mediator Model. Absolute (GFI = .96; RMSEA = .045, 90% confidence interval = .03-.06; $\chi^2/df = 1.59$) and incremental fit indices (CFI = .99; NNFI = .98) indicate a strong fit between the variance/covariance matrix for the sample data and hypothesized model. It should be noted that fit indices were derived after correlating the disturbance terms (see small

circles labeled "D" in Figure B.4.) associated with phonological and visuospatial memory ($r = .35$, $p<.05$). This technique is recommended (cf. Kline, 1998) to help control for unexplained variance (error) common to both latent variables (i.e., both were computer paradigms and administered individually).

Inspection of the pathways indicates that central executive functioning shows a similar level of continuity with both phonological ($\beta = .35$, $p<.05$) and visuospatial ($\beta = .22$, $p<.05$) memory after accounting for its shared relationship with intelligence ($r = .15$, $p<.05$). The similarity of association between central executive functioning and the two memory systems is consistent with Baddeley's (1997) model, and confirmed by constraining the two pathways to be equal. The imposition of constraints did not weaken the model relative to an unconstrained model and indicates that the two pathways are of a similar magnitude. The central executive's influence on long-term scholastic achievement, however, becomes negligible ($\beta = .05$) and non-significant when the mediating effects of phonological and visuospatial memory are included in the model.

Examination of the model reveals that visuospatial memory is not significantly related to either early ($\beta = -.02$, ns) or long-term scholastic achievement ($\beta = .03$, ns). This finding was confirmed by constraining the visuospatial to long-term scholastic achievement and visuospatial to early scholastic achievement pathways to zero. The imposition of constraints yielded no significant effect on the model relative to an unconstrained model. Thus, the continuity between central executive functioning and long-term scholastic achievement is achieved entirely by its indirect relationship with early scholastic achievement ($\beta = .17$, $p<.05$) and phonological memory ($\beta = .35$, $p<.05$), which in turn, show strong continuity with long-term scholastic achievement.

Intelligence is related to phonological ($\beta = .27$, $p<.05$) but not visuospatial memory ($\beta = .12$, ns) after accounting for its correlation with central executive functioning ($r = .15$, $p<.05$). IQ's direct relationship with long-term scholastic achievement was attenuated and no longer significant ($\beta = .07$, ns) in the mediator model relative to the baseline model. Examination of the figure suggests that the mediating effects of phonological memory and the system's direct ($\beta = .29$, $p<.05$) and indirect effect ($\beta = .33$, $p<.05$, $\beta = .48$, $p<.05$, for phonological memory to early scholastic achievement and early scholastic achievement to long-term scholastic achievement, respectively) on long-term scholastic achievement attenuated the association between IQ and both early and long-term scholastic achievement (i.e., compare the IQ to early [$\beta = .49$ to .39] and long-term [$\beta = .12$ to ns] scholastic achievement coefficients in the Baseline and Mediator Models, respectively).

Comparison of the Baseline and Mediator Models reveals two additional findings of interest. The significant relationship between central executive functioning and long-term scholastic achievement observed in the Baseline Model was negligible (.05) and nonsignificant in the Mediator Model. Second, the disturbance term indicating error of prediction (i.e., unexplained variance) in long-term scholastic achievement is smaller in magnitude in the Mediator Model (.43) than in the Baseline Model (.45), indicating that the former explains a slightly greater proportion of variance in long-term achievement (i.e., 82% vs. 80%). The chi-square difference test resulted in values of 64.829(50), significant at $p\leq.10$ but not at $p\leq.05$, indicating that the Mediator Model is not a significant improvement ($p>.05$). Finally, both fit indices that favor parsimonious over

less parsimonious ones while adjusting for model complexity also support the mediator model (i.e., lower RMSEA and higher NNFI values).

CHAPTER 4. DISCUSSION

The present study invoked Baddeley's (1997) empirically based model as a framework for investigating whether phonological and visuospatial working memory subsystems mediate attention deficit and intelligence effects on children's scholastic achievement. A baseline model was constructed based on extant literature demonstrating that intelligence and attentional indices of central executive functioning are related (Primi, 2002; Stankov, 1983; Swanson & Cooney, 1989) and traditionally show moderate to strong continuity with indices of near-term and distal scholastic achievement (Arcia, Ornstein, & Otto, 1991; Campbell, D'Amato, Raggio, & Stephens, 1991; Fergusson & Horwood, 1995). Obtained fit indices were uniformly high and support the model's hypothesized relationships. Intelligence was correlated with central executive functioning, and both variables showed significant continuity with children's early and long-term scholastic achievement after accounting for their correlated effects and controlling for relevant sociodemographic variables (i.e., age, SES). As expected, the unique contribution of IQ and central executive functioning to children's long-term scholastic achievement was primarily achieved indirectly through their influence on early achievement. This finding supports recent recommendations that initial differences in ability and achievement must be accounted for in longitudinal investigations of children's attentional difficulties (McGee, Prior, Williams, Smart, & Sanson, 2002).

A mediator model was constructed to address the primary shortcoming of the baseline model, namely, the failure to account for the process or processes by which the attention controlling central executive exerts its influence on children's scholastic achievement. Inclusion of mediator variables also may help account for the small, but

significant direct effects of the central executive and intelligence on long-term achievement if their influence is better explained by mediator variables. The inclusion of phonological and visuospatial working memory as mediators addresses these shortcomings, and is consistent with empirically based models that elucidate the processes by which the central executive exerts its influence on learning (Baddeley, 1997), and by extension, scholastic achievement.

Examination of the mediator model revealed that the association between the central executive and two working memory subsystems is consistent with hypotheses derived from Baddeley's (1997) model. Moderately strong associations were obtained for each of the pathways, with a slight advantage for the phonological subsystem. This finding is consistent with previous research demonstrating that performance on cognitive tasks is independently affected by the functioning of the central executive, visuospatial sketchpad, and phonological loop (c.f., Duff, 2000). Of greater interest, however, is the finding that only phonological memory was related to early and long-term scholastic achievement. The failure of the visuospatial system to contribute to achievement suggests at least two possibilities. One possibility is that the standardized tests used to measure academic achievement are constructed to primarily assess phonological knowledge. This explanation seems unlikely, however, given that both measures of achievement used in the study (i.e., KTEA, SAT) include both language and mathematical assessments. Research has shown that recitation of basic math facts does not require the phonological system (De Rammelaere, Stuy ven, & Vandierendonck, 2001; Seitz & Schumann-Hengsteler, 2000). Moreover, even simple subtraction appears to rely on the resources of the visuospatial sketchpad (Lee & Kang, 2002), and many high school level mathematics

skills are not related to phonological processes, instead relying on visuospatial and central executive functioning (Reuhkala, 2001).

A second, more likely explanation is that the preponderance of information learned and accumulated over many years of schooling is presented in a phonological manner, and requires both verbal understanding of directions and the verbal presentation of answers--both processes of the phonological loop (Baddeley & Gathercole, 1992). During the early elementary school years, children undergo a radical transformation in terms of working memory strategy--moving from primarily visual encoding to a combined visual-verbal strategy to finally the adult-like reliance on the phonological loop (Palmer, 2000; Pickering, 2001). This change could be the result of either normal development or immersion in a culture that rewards verbal prowess. While it is difficult to completely tease these variables apart, research does show that children can be trained to use phonological strategies to execute visual memory tasks (Johnston, Johnson, & Gray, 1987; Just & Carpenter, 1985). These findings suggest that the verbal nature of early education does affect the development of the phonological system.

On a biological level, there is ample evidence for the differential localization of working memory functions, with the phonological area primarily represented in the left hemisphere (Coull, Frith, Frackowiak, & Grasby, 1996; Desmond, 2001). Further, research shows brain asymmetry in ADHD, such that the left hemisphere is smaller than the right hemisphere (Castellanos, 2001), suggesting that control of phonological resources may be particularly disturbed in this disorder. Laboratory data further supports this assertion in that ADHD children show a greater deficit in performance of

phonological tasks when carrying a memory load (Norrelgen, Lacerda, & Forssberg, 1999).

The phonological subsystem's contribution to long-term scholastic achievement was achieved both directly, and indirectly through its influence on early learning. Its role as an important mediator of the central executive was firmly established by two findings. The strength of the association between the central executive and early achievement was weakened considerably, and its continuity with long-term memory achievement was rendered non-significant by inclusion of phonological memory in the model. This finding is consistent with research demonstrating that phonological memory particularly affects early vocabulary acquisition, which in turn affects later academic achievement (Gathercole, Willis, Emslie, & Baddeley, 1992). A similar pattern of results was obtained for intelligence. Its previously robust association with early scholastic achievement in the baseline model was diminished, and its continuity with long-term indices of achievement was no longer statistically significant. Moreover, these associations were confirmed with either no change or slight improvement in model fit using indices that favor more parsimonious over less parsimonious models.

The value of the present study was to elucidate two of the cognitive processes that may be involved in mediating attention deficit and intelligence effects on children's near and long-term scholastic achievement as hypothesized by the dual pathway model of ADHD (Rapport et al., 1999). In considering this goal, several caveats are in order. Our sample size was smaller than some previous studies invoking a structural equation modeling (SEM) approach, involved a non-clinical sample, was limited to a 4-year follow-up period of evaluation, and included a limited range of instruments as indicators

of phonological and visuospatial working memory, and central executive functioning. Other hypothesized functions of the central executive, such as switching, planning, and simultaneous storage (Baddeley, 1996), were not included in the model but may be necessary as its core components become better understood (Baddeley, 2001) and future models increase in sophistication and complexity. Nevertheless, our results were highly consistent with previous studies examining the relationships among the central executive, its two subsystems (Baddeley 2002; Bull & Scerif, 2001; Hitch & Baddeley, 1976) and intelligence (Colom, Flores-Mendoze, & Rebollo, 2003; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002), and provide for a strong fit between the hypothesized model and data while controlling for measurement error. It is important to point out, however, that SEM (like ANOVA or regression) cannot be used to specifically test directional hypotheses. Directional associations are distinguished from non-directional relationships either by logic, theory, or most persuasively, by research design. Thus, the strength of our hypothesized model rests on past research findings that have established relatively clear relationships among the proposed variables and constructs, but leave open the possibility that alternative models may adequately account for the observed relationships.

On a theoretical level, these data show the robust nature of the Baddeley working memory model as a means of understanding the core deficits of ADHD. Research has only begun to examine working memory as a means of understanding ADHD. The work thus far, however, is in agreement with the results presented here. Children with ADHD appear to have deficits on numerous working memory tasks (Rapport et al., 2001; Stevens, Quittner, Zuckerman, & Moore, 2002; Welsh, 2002), and deficits in working

memory may help explain the linkage between early reading difficulties and hyperactivity (McGee et al., 2002). The underlying mechanisms and processes, however, require extensive study. For example, it may be that the developmental shift from primarily accessing the visuospatial to the phonological subsystem is delayed or insufficient in children with ADHD, as it appears to occur at a time that coincides with the peak referral period for the disorder (i.e., 6-9 years of age). Inculcating working memory or other constructs (e.g., behavioral inhibition) as core deficits of ADHD, however, must extend beyond merely demonstrating between-group differences on tasks and paradigms. Research also must elaborate and demonstrate the processes by which hypothesized anatomical underpinnings are reflected in cognitive processes such as working memory, and how these processes are related to primary behavior problems (e.g., gross motor activity level, scholastic underachievement) associated with the disorder. As preliminary evidence suggests that training working memory in children with ADHD improves cognitive performance and concomitantly reduces gross motor activity (Klingberg, Forssberg, & Westerberg, 2002), our inchoate working memory model holds promise for unlocking the core deficits of ADHD.

APPENDIX A: TABLE

Table A.1. Matrix of Correlations and Standard Deviations

Table A.1. Matrix of Correlations and Standard Deviations of Measures of Intelligence (IQ), Central Executive Functioning (CEF), Phonological Memory, Visual Memory, Early Scholastic Achievement (Early SA), Long-Term Scholastic Achievement (Long-Term SA), Age, and SES.

		CEF		Phonological Memory			Visual Memory			Early SA	Long-Term SA				
Measure	IQ	BX Low	BX High	B12	B34	B56	TRND	SYM	TRNS	K-TEA	RDG	MATH	LANG	Age	SES
IQ	--														
CEF															
BX Low	.111	--													
BX High	.159	.777	--												
Phonological Memory															
B12	.212	.507	.497	--											
B34	.231	.520	.506	.680	--										
B56	.219	.527	.529	.641	.725	--									
Visual Memory															
TRND	.138	.237	.289	.334	.374	.370	--								
SYM	.127	.180	.258	.264	.325	.318	.860	--							
TRNS	.116	.061	.102	.189	.186	.194	.702	.734	--						
Early SA	.584	.062	.126	.120	.162	.202	.121	.122	.081	--					
Long-Term SA															
RDG	.329	.520	.507	.522	.570	.633	.301	.253	.130	.416	--				
MATH	.359	.508	.464	.545	.553	.595	.293	.250	.127	.385	.801	--			
LANG	.369	.441	.439	.462	.494	.513	.305	.248	.160	.496	.784	.743	--		
Age	-.133	.635	.537	.502	.540	.575	.195	.152	-.002	-.252	.525	.523	.350	--	
SES	.201	-.028	.009	.029	.026	.015	.050	-.002	.018	.247	.126	.080	.114	-.088	--
SD	13.633	20.429	18.977	2.811	3.135	3.504	17.094	16.211	15.810	15.002	45.027	51.945	38.198	2.422	1.452

Note. CEF = Central Executive Functioning; B12 = Blocks 1 & 2; B34 = Blocks 3 & 4; B56 = Blocks 5 & 6; TRND, SYM, and TRNS = Stimulus Equivalence Paradigm trained, symmetric, and transitive phases, respectively; K-TEA = Kaufman Test of Educational Achievement; RDG = SAT Reading total scaled score; MATH = SAT Math total score; LANG = SAT Language total score.

APPENDIX B: FIGURES

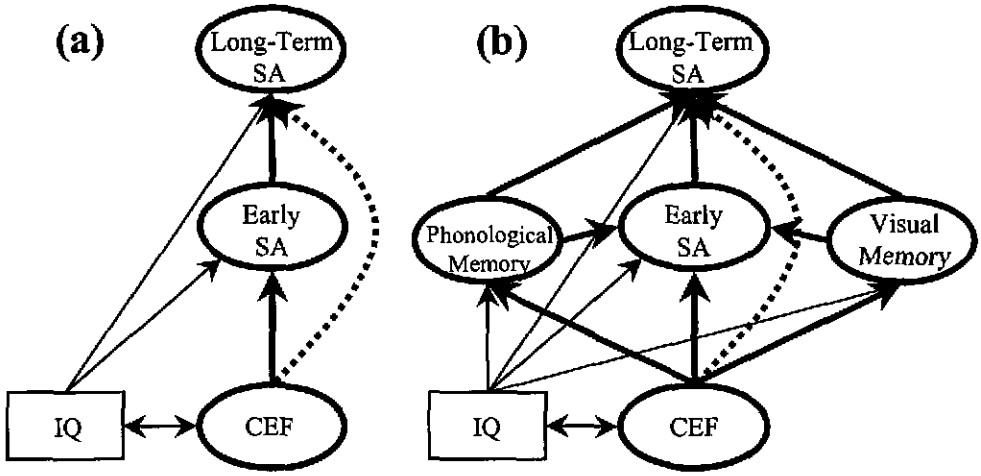

Figure B.1. Proposed baseline model (a) depicting the relationship between Central Executive Functioning (CEF), IQ, Early Scholastic Achievement (Early SA), and Long- Term Scholastic Achievement (Long-Term SA), and the proposed mediator model (b) depicting phonological memory and visual memory variables hypothesized to mediate the relationship between CEF and IQ and Early and Long-Term SA.

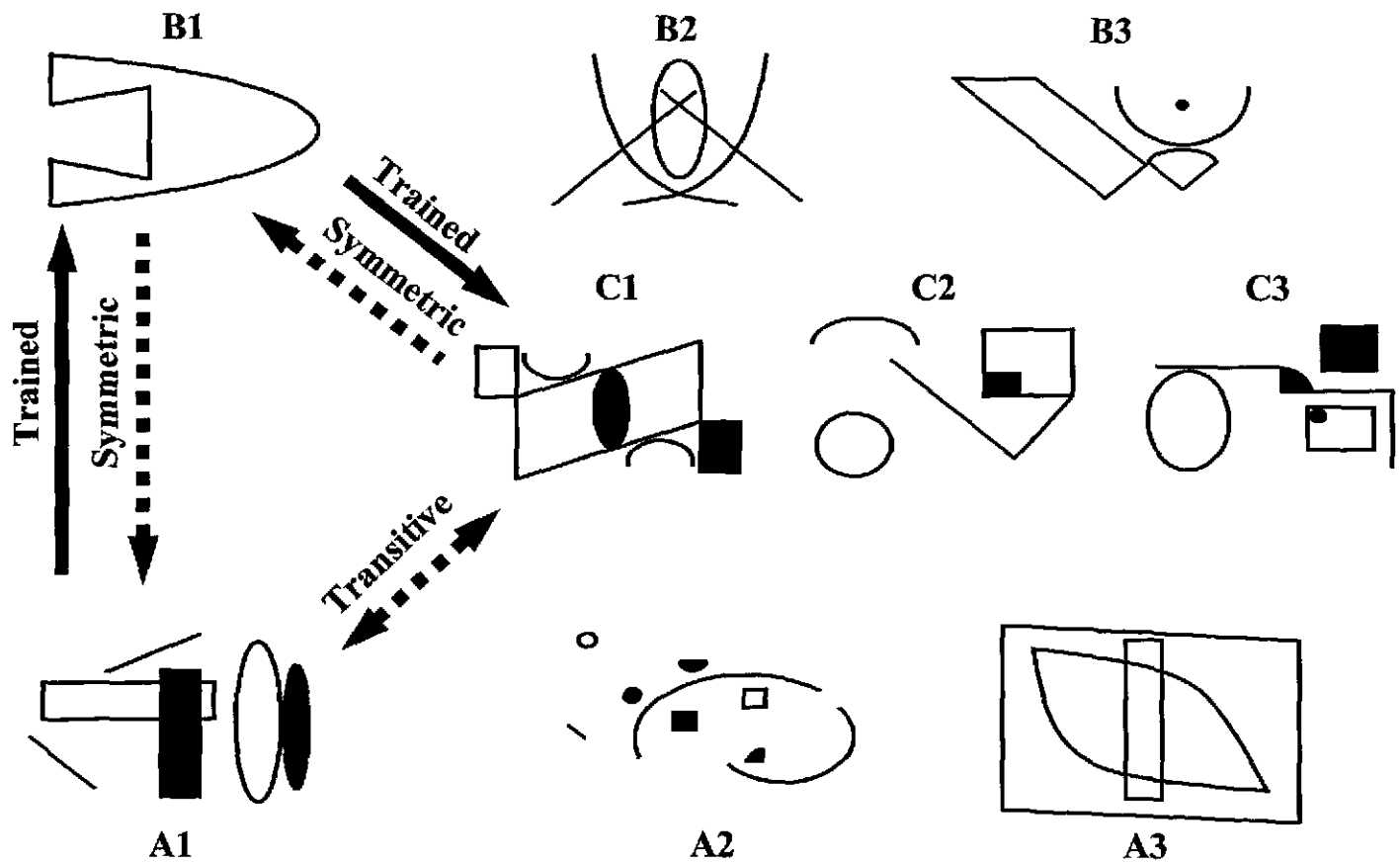

Figure B.2. Schematic depicting the Stimulus Equivalence Paradigm including sample figure groupings (A, B, & C) with trained, symmetric, and transitive relationship examples indicated by unidirectional (i.e., trained and symmetric) and bi-directional (i.e., transitive) arrows.

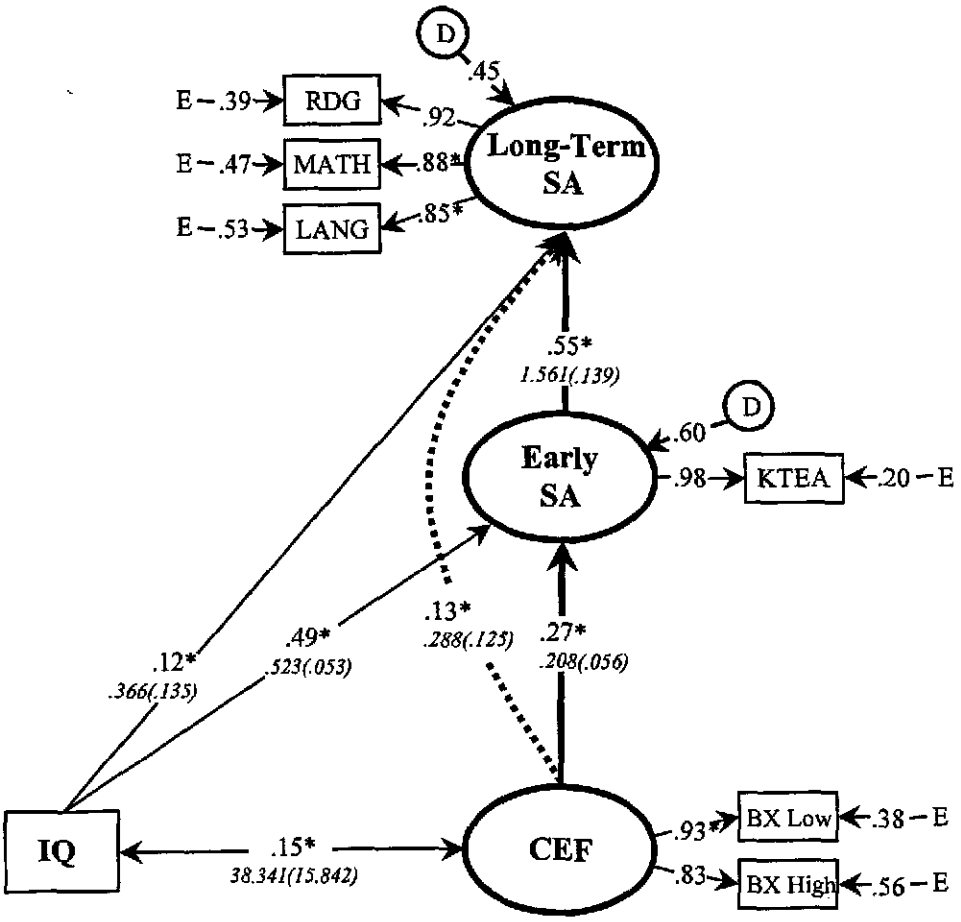

Figure B.3. Fitted Baseline Model depicting the relationships among Central Executive Functioning (CEF), IQ, Early Scholastic Achievement (Early SA), and Long-Term Scholastic Achievement (Long-Term SA). Rectangles and ovals represent manifest (measured) and latent variables, respectively. Double-headed arrows represent non-directional correlations and associated coefficients. Single-headed arrows from CEF and IQ to Early SA and Long-Term SA represent regression pathways and associated coefficients (standardized). Single-headed arrows between latent constructs (CEF, Early SA, and Long-Term SA) and their respective measured variables represent confirmatory factor analysis paths and associated factor loadings. E = measurement error. D = disturbance term. * = $p<.05$. $\chi^2/df = 2.515$. Goodness of Fit Index (GFI) = .97. Comparative Fit Index (CFI) = .98. Non-Normed Fit Index (NNFI) = .97. Root Mean Square Error of Approximation (RMSEA) = .071. Measurement of CEF was derived using the CPT BX version administered under low and high target density conditions. Measurement of IQ was derived from the matrices subtest of the Kaufman Brief Intelligence Test. Measurement of Early SA was derived from the composite score of the Kaufman Test of Educational Achievement. Measurement of Long-Term SA was derived from three composite indices of the Stanford Achievement Test (RDG = reading; MATH = math; LANG = language).

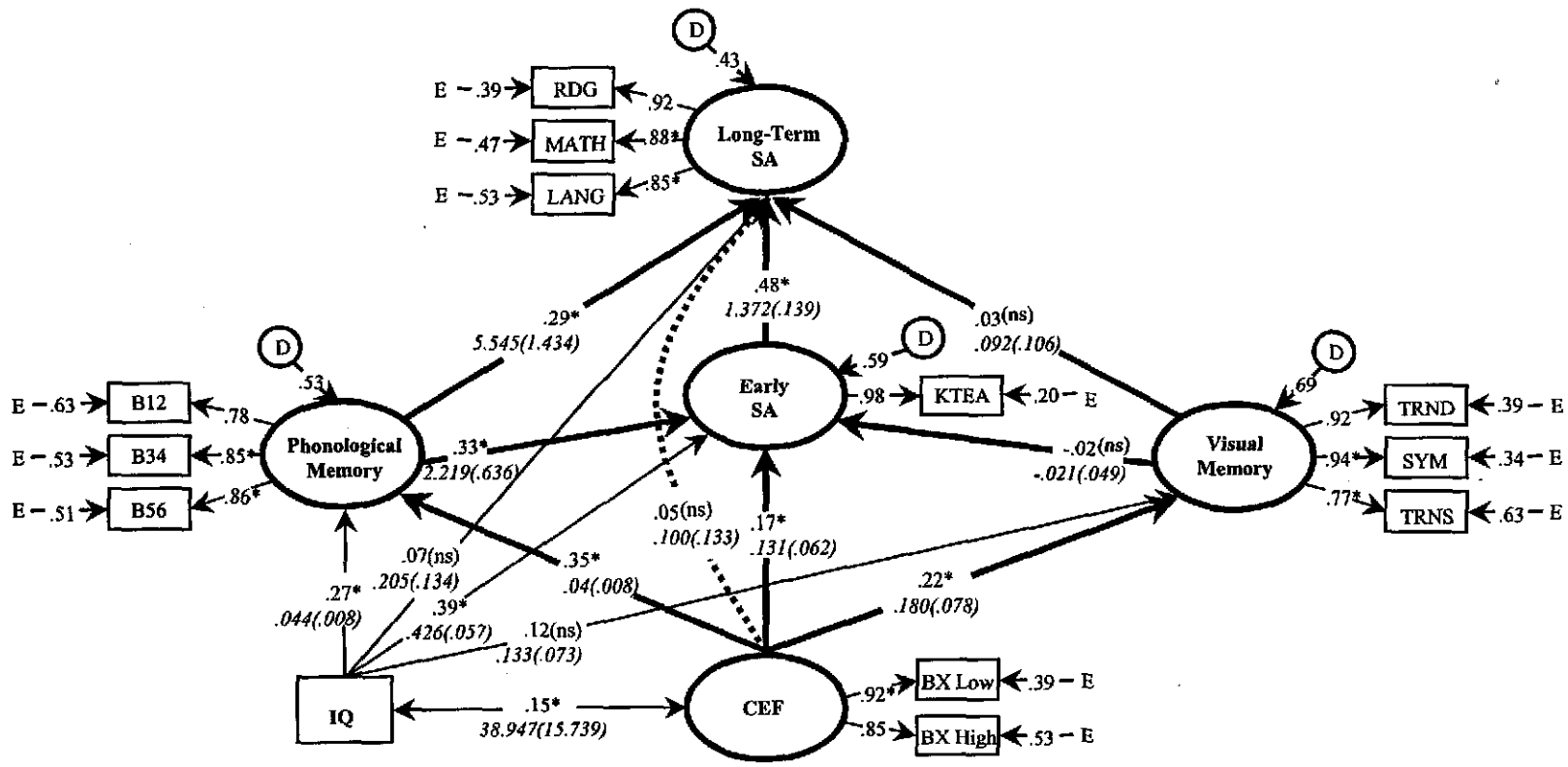

Figure B.4. Fitted Mediator Model depicting the relationships among Central Executive Functioning (CEF), IQ, Long-Term Scholastic Achievement (Long-Term SA) and the mediating influence of phonological and visual memory variables and Early Scholastic Achievement (Early SA). $\chi^2/df = 1.593$. Goodness of Fit Index (GFI) = .96. Comparative Fit Index (CFI) = .99. Non-Normed Fit Index (NNFI) = .98. Root Mean Square Error of Approximation (RMSEA) = .045. * = p<.05. E = measurement error. D = disturbance term. BX Low = CPT BX low density condition. BX High = high density condition. B12, B34, & B56 = Block combinations from the Paired Associate Learning Task. TRND, SYM, & TRNS = trained, symmetric, and transitive test conditions of the Stimulus Equivalence Paradigm. KTEA = Kaufman Test of Educational Achievement. RDG, MATH, & LANG = reading, math, and language composite indices of the Stanford Achievement Test.

FOOTNOTE

[1]A total of 325 children (146 males, 179 females) between the ages of 7 and 16 years attending 2nd through 9th grades were evaluated, however, electrical failures at the clinic caused the loss of 25 stimulus equivalence paradigm protocols (15 boys, 10 girls, all from the University Laboratory public school). Comparison of these children with the 300 participants revealed no significant changes in age, SES, ethnicity, IQ, or scholastic achievement scores.

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