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Pathways From Toddler Information Processing to Adolescent Lexical Proficiency

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Abstract

This study examined the relation of 3-year core information-processing abilities to lexical growth and development. The core abilities covered four domains – memory, representational competence (cross-modal transfer), processing speed, and attention. Lexical proficiency was assessed at 3 and 13 years with the Peabody Picture Vocabulary Test (PPVT) and verbal fluency. The sample (*N*=128) consisted of 43 preterms (<1750g) and 85 full-terms. Structural equation modeling (SEM) indicated concurrent relations of toddler information processing and language proficiency and, independent of stability in language, direct predictive links between (a) 3-year cross-modal ability and 13-year PPVT, and (b) 3-year processing speed and both 13-year measures, PPVT and Verbal Fluency. Thus, toddler information processing was related to growth in lexical proficiency from 3 to 13 years.

A long-standing issue in language development is the extent to which language emergence and growth is dependent on domain-specific factors versus domain-general ones. The domain-specific approach is tied to a modular view, where language is seen as developing according to its own specialized rules, and depending only on processes unique unto itself (Fodor, 1983). This point of view originated as a way of explaining how it was possible for young children to acquire language so quickly and seemingly without effort through mere exposure to speech, with no explicit training. It was supposed that there was a 'built-in' brain module, analogous to an instinct, which enabled the rapid acquisition of such a complex ability. Proponents of this view differ as to which components of language are encompassed within the modular view, from Fodor (1983, 2000), who considers the language system as a whole to be modular, to more restricted views, such as that of Chomsky, for whom the core of language includes only the abstract computational

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mechanisms involved in syntax, which are produced by a built-in universal grammar (Chomsky, 1988, 2011; Hauser, Chomsky, & Fitch, 2002). Pinker, on the other hand, considers a wider range of language components as built-in, including aspects of phonology, word learning, and morphology (Pinker, 1994; Pinker & Jackendoff, 2005).

Advocates of the modular view often pointed to the rare developmental disorder, Williams syndrome, where language abilities appeared to be preserved in the face of low IQ, as confirming a dissociation between language and other cognitive abilities. However, the idea that language is spared in individuals with Williams syndrome has been challenged by recent findings showing that (a) they actually have a number of language deficiencies (Brock, 2007; Karmiloff-Smith, Brown, Grice, & Paterson, 2003; Mervis & Becerra, 2007) and (b) their language ability is no better than would be predicted from their non-linguistic abilities (Mervis & Becerra, 2007).

In contrast to modular views, domain-general theories argue that language can be explained by more general principles of human cognition. One domain-general approach relies on the principles of statistical learning. It has been shown, for example, that infants can use the statistical properties of linguistic input, especially the transitional probabilities from one word (or syllable) to the next, to discover the underlying structure of sound patterns, words, and some aspects of grammar (Gomez & Gerken, 2000; Saffran, 2003). Because a similar extraction of statistical regularities is found for musical sounds and visual information (Fiser & Aslin, 2002; Saffran, Johnson, Aslin, & Newport, 1999), this ability to discover the structure underlying complex input is considered domain-general.

Another example of the domain-general approach focuses on the involvement of lexical processing speed in language learning, as exemplified by the work of Fernald and colleagues. These investigators assessed processing speed with a ‘looking-while-listening’ paradigm, where children are shown pictures of two familiar objects while hearing one of them named. The latency to look at the picture of the named target (reaction time) at 25 months was related to vocabulary growth over the second year of life (Fernald, Marchman, & Weisleder, 2013; Fernald, Perfors, & Marchman, 2006) and independently accounted for variance in linguistic ability at 8 years of age (Fernald & Marchman, 2012).

In the first comprehensive study to date examining the contribution of multiple core cognitive abilities to early language learning (Rose, Feldman, & Jankowski, 2009), we found that basic information-processing abilities from the first year of life (12 months) predicted 3-year lexical ability (vocabulary size and verbal fluency) above and beyond early-emerging language skills. This study used a battery of tasks assessing infant information processing in four domains – memory, representational competence, processing speed, and attention – many of which have previously been shown to predict other more global cognitive abilities. The results indicated that 12-month recognition memory, recall memory, and representational competence (a) were related to language at both 12 and 36 months, (b) predicted similarly for preterms and full-terms, and (c) predicted 36-month lexical proficiency independently of several other factors, including preterm birth, 12-month language, and the 12-month Bayley Mental Development Index. These findings reinforce the idea that domain-general factors are involved in early lexical acquisition.

Here, we extend this earlier work, examining (a) concurrent relations between basic cognitive abilities and lexical proficiency at 3 years, (b) the stability of lexical proficiency from 3 to 13 years, (c) predictive relations between basic cognitive abilities at 3 years and lexical proficiency at 13 years, and (d) the role of the child's early linguistic environment (as indexed indirectly by SES and maternal education) as a possible explanation for shared variance between 3-year basic abilities and 13-year lexical proficiency. We test a structural equation model (SEM) which assumes that 3-year basic cognitive abilities play a role in promoting the development of lexical proficiency, incorporating the assumptions of the domain-general view of language development. In this model, pathways from latent variables representing 3-year core cognitive abilities to 13-year lexical proficiency are expected to be significant independent of the stability of lexical proficiency over the 10-year period.

Of the four information processing abilities, memory is expected to have an independent influence on lexical proficiency because young children who have better memory are likely to be better at storing and consolidating representations of objects and events, skills fundamental to lexical development. That is, better recognition and recall memory are likely to result in memory traces that are highly discriminable and persistent and, as a consequence, more readily available to be linked to their verbal referents, resulting in faster rates of vocabulary growth.

Faster processing speed is expected to influence lexical development and lexical growth both directly, by allowing word-object and word-meaning associations to be accessed more rapidly, and indirectly, by increasing the functional capacity of working memory. Processing speed is often considered the chief factor controlling the capacity of working memory (Kail, 2007) which, in turn, has been implicated in language growth (Gathercole, Willis, Emslie, & Baddeley, 1992). Limitations in processing speed would make it difficult to keep up with the audio stream and thus interfere with building up lexical and grammatical representations essential for language development (Leonard et al., 2007).

Representational and symbolic abilities are required for the child to be able to establish the requisite arbitrary relations that exist between words and their referents. The term 'representational competence,' which refers to the ability to extract commonalties from experiences and represent them abstractly or symbolically, has been frequently assessed in young children with tasks of tactual-visual cross-modal transfer. Here, information about shape must be extracted from one modality and applied to another (Rose & Feldman, 1995; Rose, Feldman, Futterweit, & Jankowski, 1997; Rose, Feldman, & Wallace, 1988). The ability to transfer information from tactual-to-visual modalities in infancy (12 months) is related to comprehension and expression at 6 years (Rose, Feldman, & Wallace, 1992), and in preschoolers, to phonological awareness and language comprehension, assessed concurrently (Giannopulu, Cusin, Escolano, & Dellatolas, 2008).

Finally, data linking attention to language has shown that shorter look durations during infancy on habituation tasks (Bornstein & Sigman, 1986; Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004) and greater attention on distractibility tasks (Salley, Panneton, & Colombo, 2012) predict larger vocabularies. The regulation of attention is thought to foster the focused state needed to pick up language from the social interactions adults provide throughout the day. Attention and language problems are also known to co-occur frequently, especially in at-risk groups (Finneran, Francis, & Leonard, 2009; Ribeiro et al., 2011).

We will also consider the extent to which any relations found between basic information processing and later lexical proficiency are due to a common cause, namely, the child’s early linguistic environment (Hart & Risley, 1995; Hoff, 2003). These investigators found high and low socio-economic status (SES), families differed markedly in both the amount of child directed speech and the size of their children’s vocabularies. Recent work shows that the quality of speech input from the natural environment (including ‘motherese’) is a reliable predictor of language as early as 2 years (Ramirez-Esparza, Garcia-Sierra, & Kuhl, 2014), and that there is a gap between affluent and poor children in vocabulary and speed of lexical access that is already evident by 18 months (Fernald et al., 2013). In the present study, we will use SES and maternal education as indices of probable differences in the child’s early linguistic environment.

Method

Participants

The sample for the present study, participants in a prospective, longitudinal study of infant information processing, were born between February 1995 and July 1997. The original cohort consisted of *N* = 203 infants (59 preterms and 144 full-term controls). Of these, 158 (78 %) returned at 3 years (*N* = 50 preterms and 108 full-terms), and 141 at 13 years (46 preterms and 95 full-terms). The sample for the present study includes the 128 children (43 preterms and 85 full-terms) that have data on information processing measures at 3 years and on at least one of the two measures of language included in the 13-year follow-up. The institutional review board approved the protocol and signed consent was obtained at each visit from parents, and assent was obtained from all children at 13 years. Participants received a stipend of 25 dollars (plus transportation costs) for each visit.

Preterm infants were recruited from consecutive births admitted to the neonatal intensive care units of two hospitals affiliated with Albert Einstein College of Medicine. Criteria for study intake were: singleton birth, birthweight <1750 g, and the absence of any obvious congenital, physical, or neurological abnormalities. Term infants were recruited from consecutive births from the same hospitals; criteria for study intake were birthweight >2500 g, gestational age of 38–42 weeks, 5-minute Apgar scores of 9 or 10, and uneventful pre- and perinatal circumstances.

Characteristics—The demographic characteristics of the sample that returned for the 13 year visit are shown in Table 1, along with an attrition analysis, comparing those children who did and did not return at this age. The two groups were similar on all demographic factors: gender, birth order, ethnicity, maternal education, and SES, and the percentage of the sample born prematurely.

Table 1 also compares the medical risk factors at birth for the preterms who did and did not return at 13 years. Again, the two groups were similar on all factors: birthweight, gestational age, incidence of intraventricular hemorrhage, incidence of respiratory distress syndrome, 5-min Apgar score, days on ventilator and days in hospital. (For further details on medical and background characteristics in the original cohort see (Rose, Feldman, & Jankowski, 2001) .

English was the only, or the primary language spoken in the home for 89.6% of the sample. The remainder were solely (3.2%) or primarily (7.2%) Spanish speaking. (The analyses reported below were unchanged when these participants were excluded.)

Procedure

The measures considered here (given as part of larger batteries) assess different types of memory (recognition, recall), representational competence (cross-modal transfer), processing speed (psychomotor reaction time [RT]) and attention (look duration, shift rates) at 36 months, and receptive language (Peabody Picture Vocabulary Test [PPVT]) and expressive language (verbal fluency) at both 36 months and 13 years.(Measures from the larger 36-month battery were not considered here if they failed to correlate with one or more measures of language; these included short-term memory capacity, encoding speed, and anticipations.)

The tasks at 3 years were drawn from those given over two 1.5 hr testing sessions scheduled two weeks apart. Testing took place at our university laboratory, in a quiet room, with the child seated at a table and a parent seated nearby, off to the side. The extent to which procedural variation could contribute to differences across children was minimized by giving the tasks in a fixed order. The first session included one of the two recognition tasks, recall, and cross-modal transfer; the second session included the other recognition task, psychomotor speed, and language; measures of look duration and shift rate were drawn from both sessions.

To keep the child engaged, different formats were used: some tasks were presented as computerized displays, while others used 2-dimensional targets or small 3-dimensional objects; some required only visual attention whereas others engaged the child in manipulating the stimuli. All the information processing tasks were brief in duration, and breaks were given as needed.

Information Processing (3 years)

Immediate Recognition—Children’s ability to recognize faces and colorful patterns was assessed using a 9-problem battery developed in our lab (blinded reference) and a 10-problem battery developed by Fagan (Fagan & Sheperd, 1989). All problems used the visual-paired comparison paradigm (VPC) where children were familiarized with a stimulus and then tested for recognition by pairing the familiar with a novel target. In the Rose battery, five problems used black-and-white photographs of faces as targets and four used colorful abstract patterns. The Fagan battery was comprised exclusively of problems using faces. Familiarization times in both were either 5 s (faces) or 3 s (patterns); test times were 3 s throughout. Recognition memory is typically inferred from differential attention to the two test stimuli and is measured by the *Novelty Score*, the percentage of total looking time on the test devoted to the novel target. Composites for each test were created by averaging individual novelty scores. Measure: mean novelty score.

Delayed Recognition—In this task, children were habituated to three objects in succession, and then, after a delay, given a series of test trials in which each habituated object was successively paired with a new one for 4 s. This habituation-test procedure was repeated three times, with delays of 1, 3 and 5 minutes. A modified version of the infant–controlled habituation procedure was used (Diamond, Prevor, Callender, & Druin, 1997; Rose, Feldman, & Jankowski, 2004), with objects presented until the infant had two 1 s looks away. Novelty scores were calculated for each problem and averaged over all 9 problems. Measure: mean novelty score.

Recall Memory—Recall memory was evaluated using the elicited imitation task (Bauer, 2002), a task used previously with children up to 3.5 years (Riggins, Miller, Bauer, Georgieff, & Nelson, 2009). Here, the child watched the examiner model four event sequences, one at a time. (Sample 3-step sequence for ‘make a rattle:’ place small block on paddle, cover it, and then shake paddle to create rattle sound). After a 15-min delay, the child was given the props for each sequence, in turn, and encouraged to reproduce the sequences. There were four sequences, containing 5 to 12 actions each; while most actions had to be performed in a set order to achieve the desired outcome (‘enabling’), two sequences additionally contained a few actions that could be performed in any order (‘arbitrary’) (blinded reference). All sessions were coded from video for the occurrence and order of target actions. Two scores were then calculated for each event sequence: the number of target actions reproduced and the number of correctly ordered pairs of actions, considering only the first occurrence of each action (Bauer, Hertsgaard, & Wewerka, 1995). Given that the absolute number of actions varied over problems, these scores were converted to percentages for all analyses. Although the two scores tend to be highly correlated, they are generally considered separately because it is possible for a child to recall all the actions but none in the correct temporal order. The reliability of coding the occurrence of target behaviors was assessed for $n = 18$ children; for total items recalled, correlations between pairs of raters, averaged over problems, was $r = .93$; for recall of correct temporal order, $r = .97$. Measure: mean percent target actions reproduced, averaged over sequences. (Results were similar when the measure of temporal order was substituted for mean number of actions completed.)

Speed

Psychomotor Speed (RT)—Psychomotor Speed (RT), the time to orient to a stimulus, was assessed with Haith’s Visual Expectation Paradigm (VExP; (Haith, Hazan, & Goodman, 1988). In this task, eye movements are recorded as the child watches a series of pictures on a video monitor. The pictures are colorful, varied, geometric creations that move slightly up and down during the presentation period, with no accompanying sound. There were 10 baseline trials, where the left-right placement of images was random, and 60 series trials, where the images were presented in a predictable right-right-left (RRL) sequence. Stimulus durations were 500 ms; inter-stimulus intervals were 720 ms. A 150 ms cut-point separated anticipatory from reactive saccades; responses that occurred ≥150 ms after stimulus onset were scored as reaction times (blinded reference). Measures: mean RTs on baseline and series trials.

Representational Competence

Tactual-Visual Cross-Modal Transfer—This task, which assesses the ability to glean information about commonalties from experiences and represent them abstractly, required extracting information about shape by feeling an object and then recognizing it visually. There were 11 problems. On each problem, a 3-dimensional geometric form was presented tactually for familiarization (15 s), and then, on test (10 s), the previously felt object and a new one were presented visually. Novelty scores were used to index tactual-visual transfer. Measure: mean novelty score.

Attention

Look duration—Look duration, a measure of attention efficiency (with short looks associated with better attention) was assessed using measures culled from a number of different tasks: familiarization and test phases of both tasks of visual recognition memory (the ‘Rose’ and the ‘Fagan’), the test phase of cross-modal transfer, and trials from a continuous familiarization task (where two targets are presented side-by-side for a series of trials, with one target changing over presentations and the other not). Scores on each task were standardized and then averaged. There is a substantial literature showing that short looks reflect more rapid encoding (Colombo, 1993; Colombo, Mitchell, Coldren, & Freeseman, 1991; Frick, Colombo, & Saxon, 1999). Short look durations are associated with increasing age (Colombo, Mitchell, O’Brien, & Horowitz, 1987; Frick et al., 1999; Rose et al., 2001), more efficient processing (Rose et al., 2001), better visual recognition memory (Rose, Feldman, & Jankowski, 2003), and higher developmental quotients/IQ (Colombo et al., 2004; Sigman, Cohen, Beckwith, Asarnow, & Parmelee, 1991; Sigman, Cohen, Beckwith, & Parmelee, 1986). Measure: composite representing the average of the six standardized look duration scores.

Shift Rate—Shift rate, a measure capturing both efficiency of attention and comparison behavior, was assessed by calculating the number of shifts between stimuli per second (higher shift rates indicating better attention). These measures were available from all but one of the tasks used for look duration (the ‘Fagan’); scores on each task were standardized and then averaged. Faster shift rates are thought to reflect not only more rapid encoding, but also more active comparison of targets (Rose et al., 2001; Rose, Feldman, McCarton, & Wolfson, 1988; Ruff, 1975), and, like shorter look durations, are associated with increasing age (Colombo et al., 1987; Frick et al., 1999; Rose & Orlian, 2001), more efficient processing, better visual recognition memory (Rose et al., 2003), and higher developmental quotients/IQ (Colombo et al., 2004; Sigman et al., 1991; Sigman et al., 1986). Measure: composite, representing the average of the four standardized shift rate scores.

Language (36 months and 13 years)

At 36 months and 13 years, receptive language was assessed with the Peabody Picture Vocabulary Test (PPVT: Dunn & Dunn, 1981) and expressive language with an age-appropriate modification of the Educational Testing Service test of verbal fluency (Singer, Corley, Guiffrida, & Plomin, 1984). The PPVT is a standardized assessment with a mean of 100 and a standard deviation of 15.

In the Verbal Fluency test, a measure of expressive language, the child was asked to name as many things as he/she could think of in three different categories. At 36 months, the three categories were: (1) things to eat, (2) animals, (3) things that make noise; with 30 s allotted for each category. At 13 years, the categories were: (1) animals, (2) furniture, (3) fruit, with 60s allotted for category. At both ages, timing began with the first response. The child's score was the total number of items correctly listed, summed across the three categories.

For those children who were from households that were solely or predominately Spanish speaking, the language tasks at 3 years were administered in Spanish by an examiner who was fluent in Spanish. By 13 years, English was the predominant language for the entire sample.

Data analytic plan

Path models were evaluated with structural equation modeling using LISREL, with maximum likelihood estimation (Version 8.54: Jörskog & Sörbom, 2003). Univariate and bivariate distributions were initially examined for all variables, separately by group, and outlying values (2.5 SD from the mean or regression line) were Winsorized. Where necessary (e.g., for reaction times), measures were rescaled to make higher scores indicate better performance. Missing data (4.4%) were imputed using the Expected Maximization (EM) algorithm in PRELIS (Jörskog & Sörbom, 2003). Multiple indices of fit were examined (Hu & Bentler, 1998). In addition to the overall goodness-of-fit chi square (normal theory weighted least square) statistic, model fit was evaluated with the root mean square error of approximation (RMSEA; Browne & Cudeck, 1993), an absolute fit index, which ranges from 0 to infinity, and the comparative fit index (CFI; Bentler, 1990), which measures how well the sample covariance structure is reproduced by the hypothesized model. A RMSEA < .05 indicates a good fit as does a CFI > .90. Differences between tested models were evaluated with the χ^2 difference test.

Power, for SEM models, is computed in terms of comparisons of hypothesized values of goodness of fit indices to alternative values (Kim, 2005). For the path model tested here, which had 36 degrees of freedom, we used the interactive software of Preacher and Coffman (Preacher & Coffman, 2006) to calculate the power of detecting whether the hypothesized value for the RMSEA fit index of 0.05 (indicative of good fit) differed from a higher value of 0.10 (indicative of unacceptable fit) with our sample size of 128 (the number having data at 3 years and on one or both of the two 13-year language measures). With alpha set at 0.05, power was 0.98, more than ample for our purposes.

Results

Preliminary considerations

Descriptive Statistics—Preterm/full-term differences for all measures are shown in Table 2. At 3 years full-terms had significantly better recognition memory, better recall, and shorter look durations than preterms. Full-terms also had somewhat higher PPVT scores, at both 3 and 13 years, although language differences were not significant at either age.

Bivariate Relations—Correlations between information-processing measures and language measures are presented in Table 3, partialed for birth status. Initially, these correlations were obtained separately for preterms and full-terms and compared across groups, using tests of difference for independent correlations. Because none of the correlations met the criterion for a significant difference at the .05 level, the data were collapsed across birth status for all further analyses. Birth status was partialed to avoid inflation of correlations by any group differences.

As can be seen, measures of 3-year information processing from each domain were related to both language measures. First, children who had better immediate recognition and recall memory at 3 years had significantly higher 3-year PPVT and 3-year Verbal Fluency scores (pr = .22 to .41). Second, better cross-modal transfer at 3 years was also related to both 3-year language measures (pr = .27 and .22); additionally, higher 3-year cross modal scores were also related to better 13-year PPVT scores (pr = .38). Third, 3-year processing speed, as represented by post-baseline RT, was significantly related to both 13-year PPVT and 13-year Verbal Fluency (pr = .23 and .22). Fourth, while attention was only weakly related to the language measures, it was marginally related to 13-year PPVT (pr = .17).

Correlations between the two aspects of language are shown in Table 4. Within each age, correlations were fairly substantial (pr = .52 at 3 years and .42 at 13 years). These two language measures also showed significant stability over the 10-year span (pr = .58 for PPVT and .26 for verbal fluency). These results indicate that not only are these two aspects of language correlated with one another, but both show a remarkable stability from toddlerhood through adolescence.

Potential Covariates—Since the child's linguistic environment could, potentially, account for the relation between early information processing and later language we examined the relation of two indices of this factor (SES and maternal education) to all information processing and language measures. Although both indices correlated significantly with all 3 and 13-year language measures. Although both indices correlated significantly with all 3 and 13-year language measures (r = .37 to r = .52 with the PPVT and r = .20 to r = .27 with Verbal Fluency), neither SES nor maternal education correlated significantly with any of the 3-year information processing measures (r = −.03 to r = .16 and r = −.08 to r = .13, respectively). The finding that neither SES nor maternal education shared variance with any of the information processing measures implies that they could not have accounted for any of the variance the toddler measures shared with later language.

Modeling Pathways from 3-year information processing to 13-year lexical proficiency

SEM was used to test the hypothesis that 3-year information processing would relate to later lexical proficiency independently of early lexical proficiency. In this model, the 3-year information processing abilities – attention, processing speed, memory, and representational competence – were represented as latent variables, with representational competence having but a single indicator (cross-modal transfer). At both ages, 3 and 13 years, receptive proficiency was represented by single-indicator latent variables (the PPVT) as was expressive proficiency (Verbal Fluency). Direct paths were specified from (a) all 3-year information-processing abilities to both 3-year lexical factors, (b) all 3-year information-processing abilities to both 13-year lexical factors, and (c) 3- to 13-year lexical factors. The two lexical measures were allowed to correlate within each age, as were attention and speed at 3 years.

The results are depicted in Fig. 1, with solid lines indicating significant paths and lighter, dashed lines indicating non-significant ones. Standardized path coefficients, which allow for comparisons between paths, are shown, along with their significance level. (Disturbance terms are not shown.) This model provided an excellent fit to the data, $\chi^2(36) = 33.54$, $p = .58$, RMSEA = 0.0, CFI = 1.00.

Pathways from 3-year information processing to 3-year lexical proficiency—Several points are noteworthy. First, as shown by the significant path coefficients in Fig. 1, 3-year memory and 3-year cross-modal transfer both made independent contributions to 3-year PPVT ($\beta = .62$ and $\beta = .26$, respectively). In addition, these same two 3-year information processing abilities – memory and cross-modal transfer – also related independently to 3-year Verbal Fluency ($\beta = .69$ and $\beta = .18$, respectively). Neither attention nor processing speed had significant independent relations to either 3-year language measure.

Pathways from 3-year information processing and lexical proficiency to 13-year lexical proficiency—There were significant *direct* paths from two of the 3-year information processing factors – cross-modal transfer and processing speed – to 13-year PPVT ($\beta = .26$; $\beta = .34$), as well as from 3-year PPVT scores ($\beta = .57$). These results for the core cognitive abilities are important here, since they indicate that early information processing abilities have independent contributions to later lexical proficiency, even after controlling for stability in language over this period.

There was also a significant *direct* path from 3-year processing speed to 13-year Verbal Fluency ($\beta = .31$). It should be noted that, although processing speed had no independent relation to concurrent language, it was a significant factor in the growth of both aspects of lexical proficiency.

If one considers total effects, which include indirect as well as direct effects, not only do 3-year cross-modal transfer (.39, $p < .01$) and speed (.27, $p < .05$) relate to 13-year PPVT, but so does 3-year memory (.36, $p < .01$), with most of the effect of memory being indirect, going through 3-year PPVT. Speed was the only 3-year factor to have a significant total effect on 13-year Fluency (.29, $p < .05$).

Alternative model—The model above was contrasted with an alternative that assumed all the 3-year effects of information processing on 13-year lexical proficiency to be exclusively indirect, mediated by their effects on 3-year lexical proficiency. This alternative model had the same latent variables and paths as the original, but had *no* direct paths from 3-year information processing variables to the two 13-year language variables. While this model, which was nested within the original, also fit the data, with $\chi^2(44)=55.75$, $p=.11$, RMSEA= 0.046, CFI=0.95, the original model fit significantly better, as indicated by a chi-square difference test between the models, $\Delta\chi^2(8)=22.21$, $p < 0.05$.

Taken together, then, it is clear that, early information processing relates not only to concurrent lexical proficiency but also to the growth in lexical proficiency from toddlerhood to adolescence.

Discussion

The present study is the first to show that information processing in toddlerhood relates to lexical proficiency 10 years later, in adolescence. In this study, information processing was assessed at 3 years with measures drawn from four domains – memory, representational competence, processing speed, and attention – while lexical proficiency was assessed at 3 and 13 years with the PPVT and a test of Verbal Fluency. Using SEM to model relationships, we found significant links not only between information processing and concurrent lexical proficiency, but also significant direct paths from 3-year information processing to lexical proficiency at 13 years. These findings provide robust evidence for the continuing and far-reaching relation between early core cognitive abilities and later lexical proficiency. They also replicate and extend earlier work, using different methods, which had shown similar links between 1-year assessments of information processing and 3-year language (Rose et al., 2009).

There were three noteworthy findings. *First*, two aspects of 3-year information processing, memory and cross-modal transfer, made independent contributions to 3-year PPVT and 3-year Verbal Fluency. *Second*, early information processing showed a privileged relation to lexical growth, with 3-year information processing factors making contributions to language that were detectable 10 years later, and *independent* of continuity in linguistic proficiency itself. This was seen most clearly by the presence of significant direct paths (a) from 3-year cross-modal transfer and 3-year processing speed to 13-year PPVT, and (b) from 3-year processing speed to 13-year Verbal Fluency. *Third*, the substantial total effects of memory, cross-modal transfer, and speed on 13-year PPVT and Verbal Fluency underscore the considerable relation of 3-year information-processing to later lexical proficiency.

These findings are in line with those of other investigators who have examined the role of domain-general factors in language development. They extend earlier results from our own lab, showing that 12-month assessments of these same core abilities predicted lexical proficiency at 3 years (Rose et al., 2009). They also support the links between processing speed and language reported by Fernald and colleagues, who showed that the speed with which 18 to 25-month-olds recognized familiar words related to vocabulary growth at 2 years (Fernald et al., 2006) and language proficiency at 8 years (Fernald & Marchman, 2012). Additionally, they reinforce the links between early recognition memory and later receptive language that have been found in a number of studies (Fagan & Detterman, 1992; Fagan, Holland, & Wheeler, 2007; Fagan & McGrath, 1981; McCall & Carriger, 1993; Rose & Feldman, 1995; Rose et al., 1992; Rose, Feldman, Wallace, & Cohen, 1991; Thompson, Fagan, & Fulker, 1991). Finally, these results are consistent with work in older populations linking processing speed to vocabulary growth (Kail, 1991; Kail & Hall, 1994; Kail & Salthouse, 1994). Overall, our findings, along with those of these other recent studies, make clear that language growth is not exclusively governed by domain-specific mechanisms, but instead is subject to some of the same domain-general organizing principles that influence other areas of human cognition. A rapprochement between the modular and domain-general views has recently been proposed by Newport Newport, 2011).

One important question about the development of language proficiency has to do with its dependence on the child's early language environment. Weisleder and Fernald (2013) examined this issue in a recent study carried out with Spanish-speaking families of low SES. They found that the effect of child directed speech on expressive vocabulary development at 24 months was mediated by infants' language proficiency (processing speed) at 19 months. By contrast, the non-linguistic basic information processing abilities we used were unrelated to SES or maternal education (and thus unlikely to be related to the child's early language environment). Our results extend those of Weisleder and Fernald, suggesting that (a) language is influenced not only by speed of linguistic processing, but also by several non-linguistic information processing abilities (memory, representational competence, as well as non-linguistic aspects of speed), and (b) these more general information processing abilities are likely to be independent contributors to language growth. It should be noted, however, that although the basic abilities examined here were unrelated to SES or maternal education, this does not mean that they are immutable. Indeed, there is growing evidence that basic information processing abilities are improved, and their efficiency enhanced, by targeted interventions (Jankowski, Rose, & Feldman, 2001; Rueda, Checa, & Combita, 2012; Wass, Porayska-Pomsta, & Johnson, 2011).

Our study does have several limitations. First, we had only a single task of cross-modal transfer. While this task entailed tactual-visual linkages, rather than auditory-visual ones, growing evidence suggests that many of the cortical neurons involved in cross-modal relations are multisensory, and respond to sight and sounds, as well as to touch (Wallace, Carriere, Perrault Jr, Vaughan, & Stein, 2006; Wallace, Ramachandran, & Stein, 2006). The existence of multi-modal neurons raises the possibility that the specific modalities involved are not critical for the ability to form unified and abstract or symbolic representations. Second, the data are correlational in nature. While our findings are consistent with the causal model proposed, the directional arrows at 3 years could go the other way, and the possibility exists that some unmeasured factors might account for the relations observed. Third, we examined only two aspects of language. The role that basic information processing abilities play in other aspects of language, including grammatical development, remains to be explored. And finally, we used a largely monolingual sample. Since dual language learners differ from monolinguals on a number of early language parameters (Garcia-Sierra et al., 2011), it remains to be determined whether the role of information processing in the development of lexical proficiency differs in bilingual children as well.

Overall, our findings, based on a relatively large and diverse sample, show that (a) core information processing abilities from 3 years of age have a direct relation to lexical proficiency at 13 years, and (b) the relation remains significant over this 10-year period even after controlling for earlier language development.

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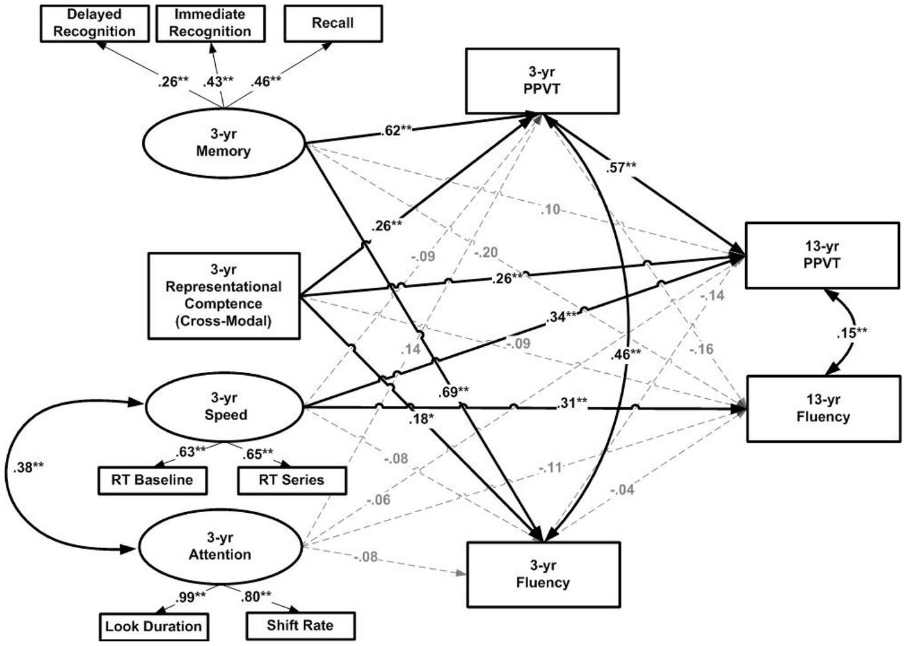

Figure 1.

SEM model of pathways from information processing and lexical proficiency at 3 years to lexical proficiency at 13 years. Ovals represent multiple-indicator latent factors; rectangles represent single-indicator latent factors and individual indicators. Single-headed arrows represent paths by which latent factors influence observed measures and each other. Solid lines indicate significant paths ($p < .05$), while dotted lines indicate non-significant ones. Curved double-headed arrows represent correlations. Parameter estimates are shown for the completely standardized solution.

* $p < .05$; ** $p < .01$. PPVT = Peabody Picture Vocabulary Test; RT = Reaction time.

Table 1

Attrition Analysis: Children Who Did and Did Not Return at 13 years

	Returned	**Not Returned**	***X^2 / t***	***P(2-tailed)***
Demographic Characteristics	**(*N*=141)**	**(*N*=62)**		
SES (Hollingshead 4 Factor Index) (M ± SD)	35.2 ± 13.2	34.2 ± 10.6	.53	.60
Maternal Education (years) (M ± SD)	13.4 ± 2.3	13.0 ± 2.0	1. 11	.27
Male (%)	49.6	53.2	.22	.65
Birth Order: First Born (%)	36.9	33.9	.17	.68
Race/Ethnicity: Black (%)	42.6	40.3	.10	.96
Hispanic (%)	44.0	45.2		
White/Other (%)	13.5	14.5		
Birth Status: Premature (%)	32.6	21.0	2.84	.10
Medical Characteristics of Preterms	**(*N*=46)**	**(*N*=13)**		
Birth weight (g)	1118.0 ± 255.3	1014.9 ± 284.4	1.25	.22
Gestational age at birth (weeks)	29.5 ± 2.8	29.9 ± 3.6	.43	.67
Intraventricular Hemorrhage (%)[a]	45.7	61.5	1.02	.36
Respiratory Distress Syndrome (%)	52.2	46.2	.15	.76
5-Minute Apgar Score (M ± SD)	7.4 ± 1.5	7.9 ± 0.9	1.41	.17
Time on Ventilator (days) (M ± SD)	7.7 ± 11.5	11.8 ± 20.5	.94	.35
Time in Hospital (days) (M ± SD)	53.1 ± 23.2	54.4 ± 26.8	.17	.87

[a] Less than half the preterms had any bleeds, and most of those would be considered mild (Grade 1 or 2).

Table 2

Descriptive Statistics

	Full-terms			Preterms			
	N	*M*	*SD*	*N*	*M*	*SD*	*t*
3-Year Information-Processing							
Memory							
Visual recognition memory [a] (% Novelty)	85	60.21	5.26	43	57.52	5.38	2.71**
Delayed Recognition (% Novelty)	73	62.30	8.00	38	63.66	6.26	.92
Recall memory (% Correct)	79	77.84	16.33	42	70.87	18.19	2.08*
Representational Competence							
Cross-modal transfer (% Novelty)	83	48.27	4.60	41	46.69	6.21	1.60
Attention							
Mean look duration (composite) [b]	85	−.07	0.57	43	.18	.63	2.25*
Shift rate (composite)[b]	85	.03	0.78	43	−.19	.59	1.58
Speed							
Reaction time (VExP baseline in ms)	78	208.18	29.22	38	204.68	30.30	.60
Reaction time (VExP post baseline in ms)	83	229.88	30.87	39	230.34	32.13	.08
3-Year Language							
Peabody Picture Vocabulary Test (PPVT)	76	87.39	15.51	35	82.06	17.12	1.63
Verbal Fluency	79	3.77	3.10	36	4.64	3.63	1.32
13-Year Language							
Peabody Picture Vocabulary Test (PPVT)	84	101.50	13.54	43	97.93	15.36	1.34
Verbal Fluency	81	12.71	2.83	43	12.79	2.68	.16

† $p < .10$;

* $p < .05$;

** $p < .01$ (2-tailed).

Note. VExP = Visual Expectation Paradigm.

[a] A composite formed by averaging the two recognition-memory batteries.

[b] An average of variables standardized to a mean of 0.

Table 3

Correlations of Early Information Processing With Language at 3 and 13 years

	3-Year Language		*13-Year Language*	
Information Processing	**PPVT**	**Fluency**	**PPVT**	**Fluency**
3-Year Measures				
Memory				
Visual recognition memory[a]	.22*	.41***	.13	.10
Delayed recognition	.18†	.08	.14	.09
Recall memory	.25**	.34***	.17†	.15
Representational Competence				
Cross-modal transfer	.27**	.22*	.38***	.12
Attention				
Mean look duration [b]	.09	.09	.17†	.06
Shift rate [b]	−0.02	−.01	.14	.06
Speed				
Reaction time (VExP baseline in ms)	−0.06	0.10	0.13	0.12
Reaction time (VExP post baseline in ms)	0.00	0.10	0.23*	0.22*

$^{\dagger}p < 0.10$;

$^{*}p < 0.05$;

$^{**}p < 0.01$;

$^{***}p < 0.001$ (2-tailed).

Notes: Correlations partialed for birth status using pairwise deletion; n=102 – 127; PPVT = Peabody Picture Vocabulary Test; VExP = Visual Expectation Paradigm.

[a] A composite formed by averaging measures from the two recognition-memory batteries.

[b] An average of variables standardized to a mean of 0.

Table 4

Correlations Among Receptive and Expressive Language Measures

	3-yr Verbal Fluency	**13-yr PPVT**	**13-yr Verbal Fluency**
3- yr PPVT	.52[***]	.58[***]	.25[**]
3- yr Verbal Fluency		.36[***]	.26[**]
13- yr PPVT			.42[***]

[**] $p < 0.01$;

[***] $p < 0.001$.

Note. – Correlations partialed for birth status; PPVT = Peabody Picture Vocabulary Test