HARTLEY, J. and DAVIES, I.K. (1976) Preinstructional strategies: The role of pre-tests, behavioral objectives, overviews and advance organisers. *Review of Educational Research*, 48, 239–265.
HUDSON, T. (1982) The effects of induced schemata on the 'short circuit' in L2 reading: Non-decoding factors in L2 reading performance. *Language Learning*, 32, 1–31.
JOHNSON, P. (1981) Effects on reading comprehension of language complexity and cultural background of a text. *TESOL Quarterly*, 15, 169–181.
JOHNSON, P. (1982) Effects on reading comprehension of building background knowledge. *TESOL Quarterly*, 16, 503–516.
KOH, M.Y. (1985) The role of prior knowledge in reading comprehension. *Reading in a Foreign Language*, 3, 375–380.
LUITEN, J., AMES, W. and ACKERSON, G. (1980) A meta-analysis of the effects of advance organisers on learning and retention. *American Educational Research Journal*, 17, 211–218.
MAYER, R.E. (1984) Aids to text comprehension. *Educational Psychology*, 19, 30–42.
MOORE, D.W. and READANCE, J.E. (1980) A meta-analysis of the effect of graphic organisers on learning from text. In M.K. Kamil and A.J. Moe (eds.). *Perspectives on Reading Research and Instruction. Twenty-ninth Yearbook of the National Reading Conference.* Washington, D.C.: National Reading Conference, 213–218.
NUNAN, D. (1985) Content familiarity and the perception of textual relationships in second language reading. *RELC Journal*, 16, 43–51.
OLLER, J.W. (1979) *Language Tests at School.* London: Longman.
PERKINS, K. (1983) Semantic constructivity in ESL reading comprehension. *TESOL Quarterly*, 17, 19–27.
STEFFENSEN, M. (1986) Register, cohesion and cross-cultural reading comprehension. *Applied Linguistics*, 7, 71–85.
TUDOR, I. (1986) Advance organisers as adjuncts to L2 reading comprehension. *Journal of Research in Reading*, 9, 103–115.
TUDOR, I. (1989) Pre-reading: A categorisation of formats. *System*, 17, 323–338.
WILLIAMS, E. (1984) *Reading in the Language Classroom.* London: Macmillan.
YORIO, C.A. (1971) Some sources of reading problems for foreign language learners. *Language Learning*, 21, 107–115.

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Reading, phonological skills and short-term memory: interactive tributaries of development

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ABSTRACT

Short-term memory, phonological processing and reading are associated abilities, but the causal relationships between them are yet to be determined. A longitudinal study of 40 children as they develop from 5 to 7 years old is analysed to investigate the interactive development of these skills. In children who have not yet begun to read it appears that phonological skills promote the acquisition of letter knowledge and that these two abilities, together with visual STM, lead the development of reading. The pattern changes once reading acquisition begins. LISREL analyses demonstrate that reading now promotes further growth of phonological skills and auditory STM, and these phonological skills in turn lead to the development of visual STM. The acquisition of reading makes relevant active phonological processing in short-term memory and thus stimulates the development of these skills.

RÉSUMÉ

Lecture, compétences phonologiques et mémoire à court terme: interactions tributaires du développement

La mémoire à court terme, le traitement phonologique et la lecture sont des compétences qui sont liées, mais leurs relations causales demeurent inconnues. On a effectué une étude longitudinale de 40 enfants entre 5 et 7 ans pour examiner le développement interactif de ces compétences. Chez les enfants n'ayant pas encore appris à lire il apparaît que les compétences phonologiques (segmentation en phones, segmentation en syllabes et fusion des sons) favorisent l'acquisition de la connaissance des lettres et que ces compétences, ainsi que la mémoire immédiate de

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symboles visuels ayant des équivalents sonores, ont un rôle moteur dans le développement de la lecture.

Le tableau change quand commence l'apprentissage de la lecture. Des analyses LISREL démontrent que c'est maintenant la lecture qui favorise le développement des compétences phonologiques et de la mémoire immédiate auditive, et que ces compétences phonologiques conduisent à leur tour à un développement de la mémoire à court terme visuelle.

Les données génétique provenant de la période postérieure aux débuts de l'acquisition de la lecture sont en accord avec les dernières versions du modèle de la mémoire de travail (Baddeley, 1986). La lecture est le régulateur des compétences phonologiques (SON) et l'acquisition de celles-ci entraîne à son tour un développement de la mémoire immédiate de matériaux visuels symboliques. La conscience phonologique n'a de réelle valeur pour l'enfant que quand il éprouve le besoin de lire dans un système alphabétique donné, et la lecture joue alors un rôle actif dans l'acquisition d'un système de classification phonémique d'ensemble permettant la transformation des graphèmes en phonèmes. Toutes ces acquisitions — système de classification phonémique, répertoire de correspondances grapho-phonétiques, et pratique de dénomination du matériel verbal — contribuent à une stratégie d'auto-répétition articulée des items dénommables présentés visuellement. L'enfant devient capable d'utiliser la boucle articulatoire et ceci permet un accroissement de l'empan digital visuel. Les enfants de quatre à six ans utilisent un support visuo-spatial pour mémoriser le matériel verbalisable présenté visuellement tandis que les enfants plus âgés dénomment le matériel et effectuent une auto-répétition articulée. Chi (1976) présente ces progrès de la mémoire à court terme comme un reflet du développement métacognitif: les jeunes enfants ne dénomment pas et ne verbalisent pas spontanément des symboles présentés visuellement; ils prennent plutôt en considération les propriétés visuelles du matériau. Les enfants plus âgés par contre, font bien la différence entre un matériau symbolique et un matériau non-symbolique présenté visuellement en tirant parti des associations phonologiques et lexicales du premier, en dénommant les items et en se les répétant de manière articulée. Nos résultats suggèrent que ces stratégies sont pratiquées et deviennent significatives quand commence l'acquisition de la lecture lorsque l'accent est mis sur la transformation des symboles en sons.

Nous suggérons donc qu'il existe une forte relation entre le codage phonologique des tâches de mémoire immédiate et l'apprentissage de la lecture, et que c'est l'acquisition des premières compétences de lecture qui soutend les changements génétiques dans les stratégies et les compétences mises en oeuvre dans les tâches de mémoire immédiate. L'acquisition de la lecture rend pertinent un traitement phonologique actif de la mémoire immédiate et stimule donc le développement de ces compétences.

La littérature en ce domaine a eu jusqu'ici tendance à se demander dans quelle direction s'applique la causalité. Elle s'applique dans les deux directions car une compétence nouvelle s'édifie inévitablement au début sur des compétences pertinentes déjà présentes puis, étant utilisée, est en mesure de légitimer et de rendre plus pertinentes les compétences antérieures (Istomina, 1975) et provoque ainsi un nouveau développement de celles-ci.

Au long de ce texte nous nous sommes servi de trois métaphores pour le développement des compétences: la formation d'un fleuve et d'un delta (voir Hardy, 1965), les régulateurs et les serveurs, enfin la symbiose. Il s'agit dans tous les cas d'images d'interactions réciproques d'éléments temporels. Il en est ainsi pour la croissance et le développement.

INTRODUCTION

The relation between literacy and memory has been well investigated but it is still poorly understood. With respect to short-term memory [STM], Wagner (1974) has shown that rural children with little or no formal education lagged behind in STM development, seemingly because they failed to use verbal rehearsal strategies. Wagner suggests that although 'formal schooling appears to be critical for the development of the *spontaneous* use of certain memory strategies, little is known at present as to what aspects of formal schooling affect memory development' (p. 395). Over the next thirteen years considerable evidence accumulated which identified the acquisition of literacy and phonological processing skills as key associates of STM development, yet a very thorough review of this literature by Wagner and Torgesen (1987) concludes with the need for further research: 'The question now is which aspects of phonological processing (e.g., awareness, recoding in lexical access, recoding in working memory) are causally related to which aspects of reading (e.g., word recognition, word analysis, sentence comprehension), at which point in their co-development, and what are the directions of these causal relations' (p. 192). In this paper we analyse a longitudinal study of the development of reading and reading-associated skills which has been broadly outlined elsewhere (Ellis and Large, 1986, 1988) to answer some of these specific questions.

Reading ability is typically related to short-term memory span. In adults memory span is roughly equivalent to the number of words that can be read in 1.5 seconds (Baddeley, Thomson and Buchanan, 1975). In children one of the most striking features of dyslexic children (who have reading problems) is their impaired digit span (Ellis and Miles, 1981; Vellutino, 1979). Why are these skills related?

There are a number of possible roles for a short-term working memory system in reading (see Baddeley, 1979; Carr, 1981; Jorm, 1983; and Daneman, 1987 for reviews). There is evidence to suggest a component of short-term memory, the articulatory loop, which stores a small amount of verbal information in a phonological code and which is under control of the other component, the central executive (Baddeley and Hitch, 1974). Baddeley (1978) has suggested that the articulatory loop may serve as the working storage system used in the decoding of unfamiliar words using the 'word-attack' skills of applying grapheme >phoneme conversion rules and sound blending. In this view both poor reading and limited short-term memory may reflect a deficiency in phonological processing (Shankweiler, Liberman, Mark, Fowler and Fischer, 1979). Another potential role of short-term memory in reading concerns the comprehension of sentences. Kleiman (1975) suggests that in order to extract the meaning of a phrase the reader must have stored information about previously identified words in order to relate this to the words currently being identified, and the phonological component of working memory may well serve for this storage (Slowiaczek and Clifton, 1980; Baddeley, 1979; Levy, 1978). One particular aspect of this is the comprehension of anaphora: here Daneman and Carpenter (1980, 1983) have shown that readers with small working memory spans are less accurate than readers with large spans at computing pronoun co-reference relations.

These suggestions make plausible the association between short-term memory and reading ability, but the causal relations are unclear. It cannot be concluded that memory deficit is a cause of reading retardation since STM deficit may be an effect of reading failure resultant from retarded readers having had less practice in certain cognitive skills connected with reading (Deutsch, 1978). It is also possible that there is a third factor (perhaps phonological processing skills or spelling, Cataldo and Ellis, 1988) producing both memory deficit and reading failure. Longitudinal studies which test pre-reading children's cognitive skills and relate these to their subsequent reading performance allow causal relations to be determined and the present study uses this type of design to investigate the developmental association between STM ability, phonological processing skills, and reading. But STM is not a unitary phenomenon and we must assess the range of its aspects, from the ordering of non-symbolic visual material, through non-articulatory and articulatory retention of visually presented symbolic material, to retention of auditorily presented strings of unrelated material like digits and words and meaningfully related material like sentences and instructions.

METHOD

Children were selected from five schools within a five mile radius of Colwyn Bay in North Wales during 1979/1980. Selection was conditional on the following criteria: age at initial testing between 4.9 and 5.2 years; the child was monoglot English and teaching was through the medium of English; there was no severe hearing or eyesight deficiency, nor were there signs of physical or mental handicap; the teacher reported that the child had no known emotional or family problems. They were initially assessed in their first year of school as they reached five years of age and were just beginning to show some reading ability. They were seen thereafter at twelve monthly intervals at six, seven and eight years old. Subject attrition resulted in there being 40 subjects remaining in the study at age 7 (22 girls and 18 boys).

At 5, 6 and 7 years old the 40 children were individually tested for ability on 44 variables during five sessions which each lasted some 30–40 minutes. The 44 variables included the full WISC and a variety of measures of reading, spelling, vocabulary, STM, visual skills, auditory-visual integration ability, auditory/language abilities, language knowledge, and rote knowledge and ordering ability. Full details of these tests are given in Ellis and Large (1987).

For each year's set of data the scores for all 40 children on these 44 variables were normalised by conversion to stanines, a nine-point scale with mean 5.0 and s.d. 1.96. The child who had performed best on a particular variable would thus be given the score 9, the worst would score 1. This procedure allows the scores for different tests to become comparable and a child's profile of abilities can thus be produced in the same way as is done on standard attainment tests such as the WISC. It has the additional advantage of ensuring normally distributed scores with equal variances. It also entails that the mean and variability of the scores remains the same year after year.

A broad ranging exploration of the developmental association between reading

and all these skills is given in Ellis and Large (1988). In the present study we are particularly interested in the developmental interactions between reading, STM, and phonological skills. Which skills grow from which others at each stage of development? How do these abilities arise, and how are such abilities, once developed, involved in further learning and thus in further ability development? We expect the patterns of association and growth to change over time, but we have little prior knowledge from which to delimit the important stages. The following three stages seem both sensible and practical:

(i) Pre-reading — how are phonological skills, STM and letter knowledge related before the child begins to read; how, if at all, does beginning reading develop out of these prior abilities?
(ii) 5 to 6 years old — how do these skills interact in the first year of reading?
(iii) 6 to 7 years old — and how in the second year?

THE PRE-READING SKILL PATTERN

There were just eight children who had no reading ability at 5 years old: these children were unable to read any of the words on any of the seven reading tests. This small sample does not permit powerful causal path modelling. At best we can use correlational techniques to see which of the 44 abilities assessed in pre-reading 5 years old predicted their reading abilities one year later and the small sample size dictates (i) the analyses are very conservative, and (ii) the conclusions must be viewed as tentative until there is a replication with much larger N. We will also look for the predictors of two related skills, phoneme segmentation and letter recognition.

Results

In Table 1 there is a manageable view of the early stages of the acquisition of *letter recognition skills* — it is not the case that all 44 abilities predict later letter recognition, nor is it the case that there are none. There are just 5 predictors. Three are

Table 1. Data from 8 Children with no measurable Reading on any of the tests at 5 Years old. Their abilities at 5 years old which predict (zero order correlations × 100) the following abilities at 6 years old:

Reading Schonell		Phoneme Segmentation		Letter Recognition	
Phoneme Segmentation[a]	**85**	Auditory Digit Span	68	**Phoneme Segmentation**	**78**
Visual Digit Span	**82**	Syllable Segmentation	66	Sound Blending	65
Syllable Segmentation	**80**	Phoneme Segmentation	62	Letter Recognition	65
Sound Blending	**72**	(Sound Blending — just n.s.	56)	WISC Information	63
Letter Recognition	69			Syllable Segmentation	60
Visual Digit Span & A.S.	65				
Grammatical Closure	62				

[a] Items in bold remain significant as first order correlations controlling for Full WISC IQ at 5 years old: this is a very stringent test with only 5 d.f. due to low n.

phonological skills, phoneme segmentation, syllable segmentation and sound blending, and there is the part-whole relationship where previous skills in letter recognition predict later levels. Since these phonological skills predict later letter recognition, but the reverse is not the case, we suggest that phonological awareness facilitates the acquisition of letter recognition (see Kenny, 1982 on cross-lagged correlation).

Phonological abilities seem to be a relatively independent group of skills at this stage of development — the only predictors of later phoneme segmentation all concern phonological storage or manipulation (syllable segmentation, phoneme segmentation, sound blending and auditory digit span).

In these children who started with no reading ability as such we see that the important predictors of later *reading* skill also concern phonological awareness (phoneme segmentation, syllable segmentation and sound blending). Other predictors include knowledge of the alphabet (letter recognition) and short term memory for visual symbols which have sound equivalents (visual digit span, but not visual serial ordering for nonsense patterns or auditory STM spans). It is a relatively small set of significant predictors but we must remember that we are here dealing with only a few subjects.

Discussion

Taken together, these results suggest a fairly simple, broad-brushed picture of the tributaries of beginning reading skill: one identifiable stream of phonological abilities contributes to the beginnings of letter recognition skill. These two streams then serve to swell the source of reading.

THE POST-READING-ACQUISITION PATTERN OF DEVELOPMENT

Next we consider all 40 children and chart the development of their abilities until they are 7 years old.

Method

In order to allow for causal path modelling and to simplify down from 44 variables we have identified seven cognitive abilities of interest: READING — a broad-content operational definition of reading ability which has seven constituent scales measuring the reading of nonsense words, phonologically simple and complex words, and reading comprehension; AUDITORY STM — digit, word and sentence spans; VISUAL DIGIT SPAN and VISUAL DIGIT SPAN & ARTICULATORY SUPPRESSION — these two abilities allow assessment of the child's use of articulatory rehearsal; auditory and visual STM spans are measured separately since there is evidence to suggest a developmental disconnection between these skills in the 4–8 age range (Keeney, Cannizo and Flavell, 1967; Conrad, 1971; Brown, 1977; Hulme, 1984); SOUND — a number of tasks requiring the knowledge of syllabic and phonemic constituents of words and their manipulation; we can thus determine the interrelationships between these skills and those of STM and reading; COLOUR NAMING RATE — rate of articulation has been implicated as a determining factor in both STM (Case, Kurland and Goldberg, 1982) and reading (Bowers, Steffy and Swanson, 1986); VISUAL search skills in situations which do not require naming were included to allow assessment of the interrelationship between Visual STM skills and 'pure' visual skills at different stages of development. We realize that any such a priori clustering of abilities is open to numerous specific objections, but we hope that these categories are reasonably content valid. The details of the tests are as follows:

READING [READ]

Phonically Simple D&DA: Daniels and Dyack subtest 7a. A word recognition test involving phonically regular 2 and 3 letter words.

Phonically Complex D&DF: Daniels and Dyack subtest 7F. A word recognition test involving irregular words like 'who', 'any'. Extra items were added to this test and D&DA from Coltheart's (1979) Exception and Regular words to overcome ceiling effects.

Nonsense Words D&DH: Daniels and Dyack subtest 7H. A test of the pronunciation of phonically simple nonwords like 'bim'.

'Reversible' Words D&DG: Daniels and Dyack subtest 7G. A test of the recognition of words which can be read backwards like 'saw', 'net' and words high in content of 'reversible' letters like 'b/d'.

Sentence Comprehension D&DR: Daniels and Dyack Standard Test of Reading Skill. A series of 36 questions like 'Can a dog run'. The order of difficulty of the sentences reflects phonic complexity. The child must comprehend the sentence in order to answer the question.

Schonell Reading: A word recognition test for ages 5 to 15. It is composed of 100 words, ten for each year. The words are arranged in continuous order of difficulty.

Carver Spoken-Printed: This requires the child to choose from a set of five or six alternatives the printed word which represents that spoken by the examiner.

AUDITORY STM [ASTM]

Auditory Digit Span: The child is asked to repeat a string of numbers after the experimenter has said them. The initial sequence comprises two digits. The length is stepped up until there are two successive errors at the same length.

Auditory Word Span: The child is asked to repeat a series of words ranging in length from two to five syllables.

Auditory Sentence Span: The child is asked to repeat 20 sentences ranging in length from two to 11 words.

VISUAL DIGIT SPAN [VDS]

Cards containing a series of digits are presented for the same number of seconds as there are digits on the card. The child has to recall the digits in the correct order once the card has been removed. There are three trials per length from two up to eight digits.

VISUAL DIGIT SPAN & ARTICULATORY SUPPRESSION [VDSAS]

As visual digit span except that the child was to say 'hello, hello, hello, . . .' all the time when studying the card. This was to suppress articulatory rehearsal.

SOUND [SOUN]

Syllable Segmentation: Liberman (1977). The child was to tap out with a stick the number of syllables which he could hear in each word of a list.

Phoneme Segmentation: As Syllable Segmentation but tap out the number of phonemes.

Rhyme — Odd One Out: Bradley and Bryant (1976). Sets of four monosyllabic words were spoken to the child. Three of the words had a sound in common which the other did not share. In one series the odd sound was the final phoneme, in the other it was the middle phoneme. The child was to say the 'odd one out'.
Rhyme Generation: Ten words were spoken to the child and he was to give more words rhyming with each.
Sound Blending: ITPA Sound Blending Task. Words and nonwords are spoken to the child as successive, separate sounds and the child must blend them into whole words.
COLOUR NAMING RATE [COLN]
The child was to name the color patches on a card of 40 random instances of 8 colours as quickly as possible. A mean rate score was calculated over 4 trials.
VISUAL [VIS]
Visual Closure: ITPA visual closure test. The child must find 'hidden' objects in a picture strip.
Letter Search: Two visual search tasks. 1) find the 10 instances of the target letter among a page of random letters. 2) the same for word targets and foils. A rate of search score is calculated.

Analysis

The LISREL model (Jöreskog and Sörbom, 1984; Saris and Stronkhorst, 1984) is an appropriate technique for the analysis of longitudinal change in data of this type. Linear structural equation models represent causal theories with proportional and additive effects. The variables which the model should account for are called endogenous variables, the predetermined variables which are not explained by other variables in the theory are called exogenous. The effect on the i^{th} endogenous variable from the j^{th} endogenous variable is denoted by β_{ij}. The effect on the i^{th} endogenous variable from the j^{th} exogenous variable is denoted by γ_{ij}. If the data are standardized then β and γ represent path weights such that an increase of one standard deviation (sd) in the prior variable would cause an increase of $\beta(\gamma)$ sds in the endogenous variable. Each endogenous variable has an associated disturbance term, ζ, which represents the effects of unknown variables, the effect of known but omitted variables, the randomness of human behaviour, and measurement error. The amount of variation of the i^{th} exogenous variable is denoted by Φ_{ii} and the amount of covariation of the i^{th} and j^{th} exogenous variables is denoted by Φ_{ij}, this being the observed correlation. The amount of variation in the i^{th} disturbance term is denoted by ψ_{ii}. The amount of covariation between the i^{th} and j^{th} disturbance terms is denoted by ψ_{ij}. Once a model has been formulated, the causal paths within the theory are specified, information about the covariances is obtained from the data, and LISREL estimates the causal effects and other parameters and tests the model against the data.

The type of model that we specified rests on few prior assumptions. It has few restrictions in that it assumes that *any* prior abilities may affect *any* later ones. A three variable/year example of this type is shown in Figure 1. The abilities measured at 5 years old ($x_a \dots x_c$) are the exogenous variables. We allowed all possible causal paths (γ) between these and the same abilities ($y_{a1} \cdots y_{c3}$) measured at 6 years old, and also the complete set (β) from the 6 year old variables to the 7 year old variables ($y_{a4} \cdots y_{c6}$). We also freed all possible covariation within each time-period to allow for *unexplained* covariation resultant from unknown causes operating between time-periods, thus avoiding over-estimation/inflation of the *specified* between-time-period effects in the model. (This, for example, would allow phonological abilities to affect reading or vice versa *within* each time period.)

The model specification entails that the beta and gamma weights on the causal paths reflect specific direct causal weights between the variables controlling for all indirect effects, spurious relationships and joint effects. The LISREL technique is more usually applied to confirm models where causal relationships are pre-specified, or to test between different models which assume different causal paths (e.g. Mommers (1987), who tested a priori models where only some causal paths were specified and then tuned them to better fit the data). We emphasize that we are not using LISREL in this fashion here. Our analyses are more inductive and LISREL is only being used for path analysis. This decision reflects the fact that there is no agreed causal sequence to the developmental interactions between reading, phonological awareness and STM, and different researchers have promoted and produced evidence in support of different directions of causality. Thus, for example, Liberman and Shankweiler (1979) and Bradley and Bryant (1983) consider phonic segmentation to be a prerequisite for learning to read and claim that it should be taught as an oral analytic skill before children are introduced to print. In contrast, Ehri (1979) and Cataldo and Ellis (1988) suggest that the reverse may be more true, and that children learn much about the phonetic structure of words when they learn how to interpret spellings as successful maps for pronunciations. There is also a third alternative, viz. that the two skills develop reciprocally, with phonological development facilitating early reading acquisition and in turn growing from reading skill at later stages (Ellis and Large, 1988). Bryant and Goswami (1987) review work on these different causal alternatives. The same arguments can easily be made for developmental interactions between reading and STM: early reading using strategies of grapheme-phoneme association and sound blending may capitalize on pre-existing ST working memory resource; later practice in reading, which makes extensive use of ST working memory and which promotes naming, articulatory rehearsal and retention of information in order, may in turn result in STM improvements (Ellis and Large, 1987). Jorm (1983) reviews work on these different causal alternatives. As with reading and phonological skills, as with reading and STM, so with any pair of related skills in development: we could propose a priori models for any permutation of two of the related abilities which we are measuring in this study, and argue a plausible case for a->b, b->a, z->a and b, or reciprocal causation. Given that such contradictory or complimentary alternatives exist, it would be premature to reify just one of the alternatives in a model for LISREL confirmation. In such cases as these it is appropriate that LISREL be used in an inductive fashion.

In this case we used an eight variable/year model where the gross variables were created by simply summing the scores on the constituent tests. The eighth variable is full WISC IQ, so these analyses 'take-out' any effects of intelligence. We would have preferred to use the factor analytic portions of LISREL to construct these measures as latent, error-free constructs (Jöreskog and Sörbom, 1977), but we were prevented by lack of computer resource and by a palpable shortage of replicates (just 40 children). Crano and Mendosa (1987), when similarly faced with a small subjects-to-variables ratio in their analyses of the Berkeley Growth Study, suggest

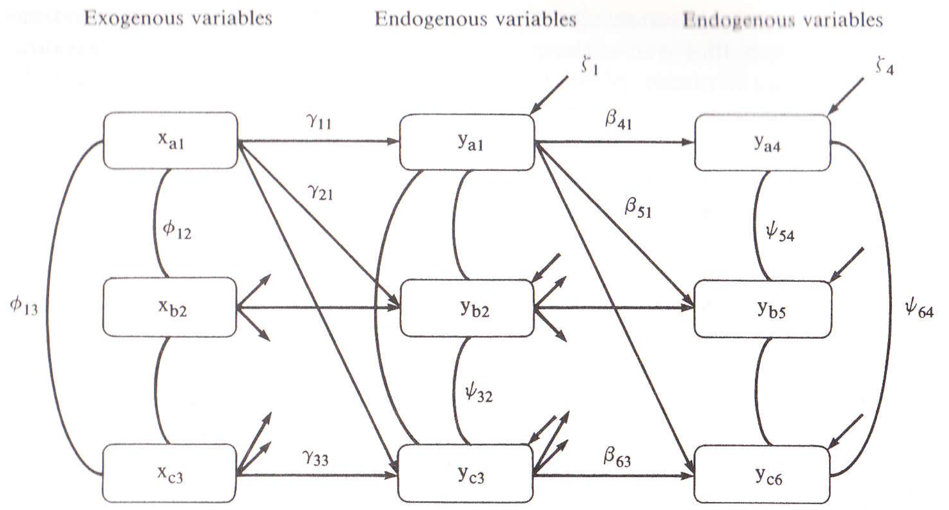

Figure 1. A three variable/year illustration of the type of LISREL model fitted to the eight variable/year longitudinal data. The three time periods run left to right. See text for details.

that summing variables shown to be like in prior correlational and factor analyses is an appropriate remedial measure to allow exploratory LISREL analyses, but they caution, as should we, that any such analyses should be regarded as preliminary to confirmatory analyses of subsequent data from studies using a larger N. The computer package LISREL VI was used to estimate the value of each parameter taking all other linking paths into account. Whatever the drawbacks of this taxonomy and its associated scaling methods, it takes us a long way towards analysis of the three years of development in terms of the *direct* contributions of these different broad classes of skill to subsequent abilities at each stage of development.[1]

Results

The resultant path coefficients are shown in Table 2. These path weights can be interpreted as follows: when all other variables and their interconnecting paths are controlled, an increase in the cause variable of one sd results in an increase of (path weight) sds of the effect variable. When we look down a column we are looking at that variable as cause of later abilities shown in the rows; when we look across a row we are looking at that variable as effect of prior abilities shown in the columns. Thus, for example, an increase of one sd in READ at age 5 is associated with an increase in SOUND skill of 0.45 sd at age 6. In contrast an increase of 1 sd in SOUND at 5 results in a mere 0.07 sd increase in READ at 6. The path weights in bold are significant at the 0.05 level.

Discussion

These data suggest a wide range of conclusions concerning the interactive development of these skills, the more pertinent are as follows:

Table 2. Data for all 40 children. LISREL path analysis of the contributions of prior skills to later ones: (Path coefficients in bold are significant at p < 0.05)

Gamma	(R^2)	IQ5	READ5	ASTM5	VDS5	VDSA5	SOUN5	COLN5	VIS5
5 TO 6 YEARS OLD									
IQ6	(72)	**44**	26	11	−12	16	10	21	−09
READ6	(66)	−16	**72**	06	04	13	07	14	−10
ASTM6	(59)	01	**31**	21	29	10	−05	18	−12
VDS6	(56)	21	11	−03	**34**	09	**39**	−22	−26
VDSA6	(76)	**39**	10	23	09	**49**	−17	−04	−10
SOUN6	(58)	17	**45**	04	−02	20	24	−01	−17
COLN6	(85)	02	14	07	−04	07	−07	**75**	14
VIS6	(62)	14	18	00	03	−03	13	−06	**53**

Beta	(R^2)	IQ6	READ6	ASTM6	VDS6	VDSA6	SOUN6	COLN6	VIS6
6 TO 7 YEARS OLD									
IQ7	(66)	**87**	−02	22	12	−17	03	−15	04
READ7	(54)	27	**57**	18	08	−11	15	03	**−24**
ASTM7	(68)	13	**36**	**46**	06	00	08	05	−15
VDS7	(49)	28	−23	**31**	**39**	−10	**41**	13	−24
VDSA7	(51)	20	16	18	26	**32**	13	−22	−25
SOUN7	(48)	10	**29**	−04	05	−05	**72**	06	−14
COLN7	(55)	07	−10	18	−06	11	**52**	**36**	−24
VIS7	(58)	**38**	**42**	05	−12	00	12	−08	**24**

–The part-whole relationship whereby later skill level is best predicted by earlier proficiency at that same skill is the most general (and at least interesting) finding. It is apparent in the bold significant diagonals.

–At each of the two developmental stages Reading skill contributes more to later proficiency in Auditory STM (0.31, 0.36) than the reverse (0.06, 0.18). Indeed Reading is the *best* predictor of Auditory STM at 6 years old (0.31), better even than prior levels of Auditory STM itself (0.21).

–At each of the two developmental stages Reading skill contributes more to later proficiency in phonological processing [SOUND] (0.45, 0.29) than the reverse (0.07, 0.15), but this is more the case in the early stages of development from 5 to 6 where again Reading is the *best* predictor of SOUND at 6 years old.[2]

–Visual search skills without naming are generally negative predictors of reading, phonological skills and all forms of STM at both stages of development. The children who are retaining a more visual or concrete strategy are those who lag behind in the acquisition of these verbal skills (no causal directions are implied).

–Auditory STM does not seem to grow out of the phonological processing skills involved in the SOUND tasks (−0.05, 0.08), but Visual STM is best predicted by prior SOUND abilities at both stages (0.39, 0.41), as is rate of articulation in the Colour naming task from 6 to 7 (0.52). This dissociation between Auditory and Visual STM is consistent with the notion that in Auditory STM tasks the phonology is *given*, whilst in Visual STM, in the naming of objects, pictures, or symbols, and in reading, the phonological referents have to be *actively created and manipulated*.

–Just as Auditory STM and Visual STM are dissociated, so also are Visual Digit Span and Visual Digit Span with Articulatory Suppression. Whereas at both stages VDS is best predicted by SOUND (0.39, 0.41), VDSAS is not at all (−0.17, 0.13).

These post-reading-acquisition results can be summarized thus: Reading is the direct pace-maker of phonological processing skills and Auditory STM (but not VDS or VDSAS). In turn these phonological abilities promote the development of Visual Digit Span (but not VDSAS).

Whilst such a cascade of development may perplex, it does accord with recent revisions of the working memory model (Baddeley, 1986). In the original working memory framework phonological coding effects in immediate serial recall of verbal items were all explained in terms of a subsidiary slave system to the central executive, the articulatory loop (Baddeley and Hitch, 1974; Baddeley et al., 1975). However, the following types of finding called for a revision of the model: (i) phonemic similarity effects for auditorily (but not visually) presented material are resistant to articulatory suppression which interferes with the articulatory loop, (ii) unattended speech causes a clear impairment in immediate memory for visually presented digits, an effect which is abolished by articulatory suppression. Salamé and Baddeley (1982) present a plausible account of this unattended speech effect whereby there are two distinct components to the articulatory loop: a phonological input store capable of representing speech for a brief period, and an articulatory control process which can refresh the representations of items in the phonological store before they fade. Speech-based information can be registered in the phonological store either by an obligatory registration through hearing spoken material or by an optional process of subvocalisation. Visually presented verbal material can only gain access to the store by subvocal rehearsal. So the account of the unattended speech effects runs thus: unattended speech gains obligatory access to the phonological store, hence corrupting the memory trace left by the visually presented items that are entered into the store through subvocal rehearsal; articulatory suppression prevents rehearsal and thus impairs overall visual STM performance and concomitantly removes the unattended speech effect by preventing access to the phonological store (Salamé and Baddeley, 1982). Baddeley and his colleagues have since gathered considerable evidence for the separability of these two components, the phonological store and the articulatory loop (Baddeley, 1986).

How does this account fit our post-reading-acquisition developmental data? Reading is the pace-maker of phonological (SOUND) skills. Both Ehri (1979) and Valtin (1984) argue that phonological awareness is only of real value to the child when he or she is confronted with the need to read from a particular alphabetic system and thus they stress how reading plays an active part in the acquisition of a comprehensive phonemic classification system which will allow grapheme to phoneme conversion. These developments, a phonemic classification system, a repertoire of grapheme to phoneme correspondences, and practice in naming verbal material, all contribute to a strategy of articulatory rehearsal of visually presented nameable items. The child becomes proficient in using the articulatory loop and this results in an improvement in Visual Digit Span (VDS). Keeney et al. (1967) and Conrad (1971) observed that 4–6 year old children use a visuo-spatial scratch pad for remembering visually presented nameable material whereas older children name the material and use articulatory rehearsal. Chi (1976) discusses these developments

in STM as reflecting metacognitive development: younger children do not naturally name and rehearse visually presented symbols, rather they deal with the material using its visual characteristics. Older children, however, do differentiate between visually presented symbolic and non-symbolic material by capitalizing on the phonological and lexical associates of the former, thus naming the items and articulatorily rehearsing them. Our results suggest that these strategies are practised and made meaningful in early reading acquisition where symbol>sound conversion is emphasized. In contrast, Visual Digit Span with Articulatory Suppression (VDSAS) is relatively unaffected by reading acquisition because the rehearsal component is actively prevented in this task.

We suggest, therefore, that there is a strong relationship between phonological coding in STM tasks and learning to read, and that it is the acquisition of early reading skill which underpins the developmental changes in strategies and skills used in STM tasks. Developmental studies of ST and working memory which ignore reading development ignore the key components. Furthermore, there is now considerable evidence implicating the important pacemaking role of spelling in this process (Frith, 1985; Cataldo and Ellis, 1989).

GENERAL DISCUSSION

The conclusions of the pre-reading analyses were that phonological skills promoted the acquisition of letter knowledge and that these two abilities, together with visual STM, led the development of reading. The conclusions of the post-reading analyses were that reading promoted the acquisition of phonological skills and Auditory STM, and that the phonological skills in turn led to the development of visual STM!

The literature on this topic thus far has tended to ask which direction of causality applies (e.g. Ehri, 1979; Bradley and Bryant, 1983; Bryant and Bradley, 1985; Bryant and Goswami, 1987). Both directions apply because a new skill invariably initially builds on whatever relevant abilities are already present, then, as it is used, it may well legitimatize and make more relevant (Istomina, 1975) those prior skills and so in turn cause their further development. Stanovich has persuasively argued the case for reciprocal relationships and bootstrapping effects: 'In short, many things that facilitate further growth in reading comprehension ability — general knowledge, vocabulary, syntactic knowledge — are developed by reading itself' (Stanovich, 1986, p. 364), 'interrelationships between the various subskills of reading and intelligence increase with age, *probably due to mutual facilitation*' (Stanovich, Cunningham and Feeman, 1984, p. 278, my emphasis). In the evolution of this present paper we have used three metaphors for skill development: river and delta formation (see Hardy, 1965), pace-makers and followers, and symbiosis. They are all images of reciprocal interactions of elements over time. Such is growth and development.

NOTES

I thank Barbara Large for gathering the data, Gordon Brown for comments on two later drafts and for the argument in Footnote 1, and the teachers and children of Colwyn Bay Infants County Primary

School, St Joseph's Aided Roman Catholic Junior School, Penrhos Junior School, and Lyndon Junior School.

1. There is, as always, the possibility of a dissociation between performance and ability (Chapman and Chapman, 1973). In the present case this might arise as a result of differential task familiarity (Baron and Trieman, 1980) and such effects threaten the interpretation of longitudinal causal path studies. Performance on any test reflects two different things: (i) the underlying competence, and (ii) the ability to bring that competence to bear on a (possibly unnatural) task. All of these analyses assume (ii) is equal for all tests. Yet if reading were a much more natural and practised task than the other tests (e.g. STM or Sound), then it would be quite possible to get the present pattern of *performance* results where READ scores are subsequently associated with higher ASTM and SOUND scores and yet in *skill competence* terms ASTM and SOUND actually lead READ: if READ is a more natural or practised test then improvements in reading could translate developmentally sooner into improvements on the READ tests; thus an improvement in, for example, phonological awareness might soon give rise to an improvement in READ scores, but it paradoxically might not show up as quickly as an improvement in the SOUND measures designed to tap that skill.

   This problem applies to all studies of different cognitive processes and at present there is no easy answer to it. Baron and Trieman (1980) suggest a number of promising moves, the best of which would make a multi-variable longitudinal study such as this very difficult to resource. One obvious ploy would be to equate tasks for practice, yet this is hopeless — (i) a child's experience does not level out the exposure to real world abilities and to the idiosyncratic and peculiar concerns of experimental psychologists, (ii) while attempting to equate tasks for familiarity we also have to control their cleanness, i.e. the specificity with which they tap the underlying ability of concern (Calfee, 1977), and their discriminating power. And even if we could equate tasks for practice then this would not be enough since we are concerned not with mere exposure but with the effects of that exposure.

   In the present study we paid as much homage to these problems as is common. We tried to make the tests as natural and as fun as possible. We tried to use stimuli which were familiar to the child. A trained and friendly teacher took trouble to put the children at ease with all of the tests. Important variables like READ and SOUND had multiple measures. Our relatively long one-year time lags are less prone to be affected than are shorter ones.

2. These findings of reading contributing to later skill levels in Auditory STM and Phonological processing more than it grows from them do not seem to be an artifact of the reliabilities of the composite measures used here: (i) IQ is a composite of more variables than Reading, yet it is no more leader than led; (ii) the general effect of paths from reading being greater than paths to reading are found if we repeat this analysis with the individual reading measures, although there are particular minor differences depending on the specific measure used.

REFERENCES

BADDELEY, A.D. (1979) Working memory and reading. In P.A. Kolers, M.E. Wrolstad and H. Bouma (eds.) *Processing of Visible Language*, Vol. 1. New York: Plenum Press.

BADDELEY, A.D. (1986) *Working Memory*. Oxford: Clarendon Press.

BADDELEY, A.D. and HITCH, G. (1974) Working memory. In G.A. Bower (ed.) *The Psychology of Learning and Motivation*. Vol. 8. New York: Academic Press.

BADDELEY, A.D., THOMSON, N. and BUCHANAN, M. (1975) Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, 14, 575–589.

BARON, J. and TREIMAN, R. (1980) Some problems in the study of differences in cognitive processes. *Memory and Cognition*, 8, 313–321.

BOWERS, P.G., STEFFY, R.A. and SWANSON, L.B. (1986) Naming speed, memory, and visual processing in reading disability. *Canadian Journal of Behavioral Science*, 18, 209–223.

BRADLEY, L. and BRYANT, P.E. (1983) Categorizing sounds and learning to read: a causal connection. *Nature*, 301, 419–421.

BROWN, R.M. (1977) An examination of visual and verbal coding processes in preschool children. *Child Development*, 48, 38–45.

BRYANT, P.E. and BRADLEY, L. (1985) *Children's Reading Problems*. Oxford, Blackwell.

BRYANT, L. and GOSWAMI, U. (1987) Phonological awareness and learning to read. In J.R. Beech and A.M. Coley (eds.) *Cognitive Approaches to Reading*. Chichester: Wiley.

CALFEE, R.C. (1977) Assessment of independent reading skills: Basic research and practical applications. In A.S. Reber and D.L. Scarborough (eds.) *Towards a Psychology of Reading*. Hillsdale, N.J.: Erlbaum.

CARR, T.H. (1981) Building theories of reading ability: On the relation between individual differences in cognitive skills and reading comprehension. *Cognition*, 9, 73–114.

CASE, R., KURLAND, M. and GOLDBERG, J. (1982) Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, 33, 386–404.

CATALDO, S. and ELLIS, N.C. (1988) Interactions in the development of spelling, reading and phonological skills. *Journal of Research in Reading*, 11, 86–109.

CATALDO, S. and ELLIS, N.C. (1989) Learning to spell, learning to read. In P.D. Pumphrey and C.D. Elliott (eds.) *Primary School Pupils' Reading and Spelling Difficulties: Current Research and Practice*. Basingstoke: Falmer Press.

CHAPMAN, L.J. and CHAPMAN, J.P. (1973) Problems in the measurement of cognitive deficit. *Psychological Bulletin*, 79, 380–385.

CHI, M. (1976) Short-term memory limitations in children: Capacity or processing difficulties? *Memory and Cognition*, 4, 559–572.

CONRAD, R. (1971) The chronology of the development of covert speech in children. *Developmental Psychology*, 5, 398–405.

CRANO, W.D. and MENDOZA, J.L. (1987) Maternal factors that influence children's positive behavior: Demonstration of a structural equation analysis of selected data from the Berkeley Growth Study. *Child Development*, 58, 38–48.

DANEMAN, M. (1987) Reading and Working Memory. In J.R. Beech and A.M. Coley (eds.) *Cognitive Approaches to Reading*. Chichester: Wiley.

DANEMAN, M. and CARPENTER, P.A. (1980) Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, 19, 450–466.

DANEMAN, M. and CARPENTER, P.A. (1983) Individual differences in integrating information between and within sentences. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 9, 561–583.

DEUTSCH, J.A. (1978) Reading disability: Methodological problems in information processing analysis. *Science*, 200, 802.

EHRI, L.C. (1979) Linguistic insights: Threshold of reading acquisition. In T.G. Waller and G.E. MacKinnon (eds.) *Reading Research: Advances in Theory and Practice*, Vol. 1. New York: Academic Press.

ELLIS, N.C. and MILES, T.R. (1981) A lexical encoding deficiency. In G.Th. Pavlidis and T.R. Miles (eds.) *Dyslexia Research and its Applications to Education*. Chichester: Wiley.

ELLIS, N.C. and LARGE, B. (1987) The development of reading: as you seek so shall you find. *British Journal of Psychology*, 78, 1–28.

ELLIS, N.C. and LARGE, B. (1988) The Early Stages of Reading: A longitudinal study. *Applied Cognitive Psychology*, 2, 47–76.

FRITH, U. (1985) Beneath the surface of developmental dyslexia. In K. Patterson, M. Coltheart and J. Marshall (eds.) *Surface Dyslexia*. London: Erlbaum.

HARDY, A. (1965) *The Living Stream*. London: Collins.

HULME, C. (1984) Developmental differences in the effects of acoustic similarity on memory span. *Developmental Psychology*, 20, 650–652.

ISTOMINA, Z.M. (1975) The development of involuntary memory in preschool age children. *Soviet Psychology*, 13, 5–64.

JÖRESKOG, K.G. and SÖRBOM, D. (1977) Statistical models and methods for the analysis of longitudinal data. In D.J. Aigner and A.S. Goldberger (eds.) *Latent Variables in Socio-Economic Models*. Amsterdam: North Holland Publishing Company.

JÖRESKOG, K.G. and SÖRBOM, D. (1984) *LISREL VI User's Guide*. Uppsala: Department of Statistics.

JORM, A.F. (1983) Specific reading retardation and working memory: a review. *British Journal of Psychology*, 74, 311–342.

KEENEY, T.J., CANNIZZO, S.R. and FLAVELL, J.H. (1967) Spontaneous and induced verbal rehearsal in recall task. *Child Development*, 38, 953–966.

KENNY, D.A. (1982) *Correlation and Causality*. New York: Wiley.

KLEIMAN, G.M. (1975) Speech recoding in reading. *Journal of Verbal Learning and Verbal Behavior*, 14, 323–339.

JORM, A.F. (1983) Specific reading retardation and working memory: a review. *British Journal of Psychology*, 74, 311–342.

KEENEY, T.J., CANNIZZO, S.R. and FLAVELL, J.H. (1967) Spontaneous and induced verbal rehearsal in recall task. *Child Development*, 38, 953–966.
LEVY, B.A. (1978) Speech analysis during sentence processing: reading versus listening. *Visible Language*, 12, 81–101.
LIBERMAN, I.Y. and SCHANKWEILER, D. (1979) Speech, the alphabet, and teaching to read. In L.B. Resnick and P.A. Weaver (eds.) *Theory and Practice of Early Reading*. Hillsdale, N.J.: Erlbaum.
MOMMERS, M.J.C. (1987) An investigation into the relationship between word recognition, reading comprehension and spelling skills in the first two years of primary school. *Journal of Reading Research*, 10, 122–143.
NEISSER, U. (1976) Memory: What are the important questions? In M.M. Gruneberg, P.E. Morris and R.N. Sykes (eds.) *Practical Aspects of Memory*. London: Academic.
SALAMÉ, P. and BADDELEY, A.D. (1982) Disruption of short-term memory by unattended speech: Implications for the structure of working memory. *Journal of Verbal Learning and Verbal Behavior*, 21, 150–164.
SARIS, W.E. and STRONKHORST, H. (1984) *Causal Modelling in Nonexperimental Research*. Amsterdam, The Netherlands: Sociometric Research Foundation.
SHANKWEILER, D., LIBERMAN, I.Y., MARK, L.S., FOWLER, C.A. and FISCHER, F.W. (1979) The speech code and learning to read. *Journal of Experimental Psychology: Human Learning and Memory*, 5, 531–545.
SLOWIACZEK, M.A. and CLIFTON, C. (1980) Subvocalisation and reading for meaning. *Journal of Verbal Learning and Verbal Behavior*, 19, 573–582.
STANOVICH, K.E. (1986) Matthew effects in reading: Some consequences of individual differences in the acquisition of literacy. *Reading Research Quarterly*, 21, 360–407.
STANOVICH, K.E., CUNNINGHAM, A.E. and FEEMAN, D.J. (1984) Intelligence, cognitive skills, and early reading progress. *Reading Research Quarterly*, 19, 278–303.
VALTIN, R. (1984) Awareness of features and functions of language. In J. Downing and R. Valtin (eds.) *Language Awareness and Learning to Read*. New York: Springer-Verlag.
VELLUTINO, F.R. (1979) *Dyslexia: Theory and Research*. Cambridge, Mass.: Erlbaum.
WAGNER, D.A. (1974) The development of short-term and incidental memory: A cross-cultural study. *Child Development*, 45, 389–396.
WAGNER, R.K. and TORGESEN, J.K. (1987) The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, 101, 192–212.

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Auditory perceptual processing in reading disabled children

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ABSTRACT

One hundred and three children attending Learning Assistance Centres due to reading difficulties and one hundred and three matched, average readers were administered a battery of auditory perceptual processing tasks. The battery was composed of auditory analysis and synthesis, auditory sequential memory, auditory discrimination, and phonemic segmentation tasks. A principal components analysis yielded four factors. These were determined to be advanced phonological awareness, sequential memory, discrimination, and simple phonological awareness. Discriminant analyses, using the factor scores, indicated that three of the four factors were able to discriminate between the able and disabled readers. Most notable among these was advanced phonological awareness. Auditory discrimination could not discriminate between the groups. The results suggest that there may not be one underlying phonological ability implicated in successful reading acquisition. Furthermore, it is clear that two levels of phonological awareness exist and that screening and diagnostic instruments should address both in order to have predictive validity.

RÉSUMÉ

La perception auditive des enfants mauvais lecteurs

Au cours de la dernière décade les chercheurs en psychologie et en éducation de la lecture ont accordé beaucoup d'attention au traitment phonologique et à la conscience de l'acte de lire. Il est maintenant admis que certaines formes de conscience phonologique ont une relation causale avec l'acquisition de la lecture et que

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