that they built up Stage 2 with poorly consolidated marl-like sediments brought from upland quarries.

Our research did not reveal conclusive evidence that the prehistoric Maya returned to farm at this location[5]. The ceramics, which in our sample ranged from terminal Preclassic to terminal late Classic types, might be attributed to the presence of settlement in the area rather than to the activity of farmers as Puleston thought. The concentrations of macrofossils and pollen of economic plants characteristic of units VI–IX were lacking. Units II–V, which were very low in organic N, total P and extractable K, were infertile compared with the soil of units VI–IX. The calcium carbonate peak at the 60-cm depth (Fig. 3) corresponds to a zone of mollusc deposition with a relative abundance of species similar to that found in units IV and V. This suggests that this zone of unit II was also deposited under permanent shallow water. The gypsum distribution is consistent with natural deposition. Our analysis of Rio Hondo water showed that it is nearly saturated with respect to gypsum. In the dry season when evapotranspiration exceeds precipitation, gypsic ground waters move upward through the soil profile depositing gypsum.

Funding was provided by the Title XII Strengthening Grant and the International Agriculture Programs of the College of Agriculture, University of Minnesota, by Florida State University and by the Wenner-Gren Foundation for Anthropological Research, Inc. This paper was written while M.P. was a Tinker Foundation postdoctoral fellow.

Received 25 October; accepted 18 November 1982.

1. Puleston, D. E. in *Social Process in Maya Prehistory* (ed. Hammond, N.) 449–467 (Academic, New York, 1977).
2. Wright, A. C. S. *et al. Land in British Honduras* Colonial Research Publ. 24 (1959).
3. High, L. R. Jr in *Carbonate Sediments, Clastic Sediments and Ecology* (eds Wantland, K. W. & Pusey, III, W. C.) 53–96 (American Association of Petroleum Geologists, Tulsa, 1975).
4. Wilk, R. R. thesis, Univ. Arizona (1981).
5. Antoine, P. P., Skarie, R. L. & Bloom, P. R. in *Maya Subsistence* (ed. Flannery, K. V.) 227–236 (Academic, New York, 1982).

Categorizing sounds and learning to read—a causal connection

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Children who are backward in reading are strikingly insensitive to rhyme and alliteration[1]. They are at a disadvantage when categorizing words on the basis of common sounds even in comparison with younger children who read no better than they do. Categorizing words in this way involves attending to their constituent sounds, and so does learning to use the alphabet in reading and spelling. Thus the experiences which a child has with rhyme before he goes to school might have a considerable effect on his success later on in learning to read and to write. We now report the results of a large scale project which support this hypothesis.

Our study combined two different methods. The first was longitudinal. We measured 403 children's skills at sound categorization before they had started to read, and related these to their progress in reading and spelling over the next 4 yr: at the end of this time the size of our group was 368. The second was intensive training in sound categorization or other forms of categorization given to a subsample of our larger group. We used both methods because we reasoned that neither on its own is a sufficient test of a causal hypothesis and that the strengths and weaknesses of the two are complementary. Properly controlled training studies demonstrate cause–effect relationships, but these could be arbitrary; one cannot be sure that such relationships exist in real life. On the other hand longitudinal studies which control for other variables such as intelligence do demonstrate genuine relationships; but it is not certain that these are causal. For example simply to show that children's skills at categorizing sounds predict their success in reading later on would not exclude the possibility that both are determined by some unknown *tertium quid*. Thus the strength of each method makes up for the weakness of the other. Together they can isolate existing relationships and establish whether these are causal.

This combination of methods has not been used in studies of reading or, as far as we can establish, in developmental research in general.

Initially we tested 118 4-yr-olds and 285 5-yr-old children (Table 1) on categorizing sounds. None of the children could read (that is, were able to read any word in the Schonell reading test). Our method, as before[1] was to say three or four words per trial, all but one of which shared a common phoneme (Table 2): the child had to detect the odd word. There were 30 trials. In such a task the child must remember the words as well as categorize their sounds. To control for this we also gave them 30 memory trials: the child heard the same words and had to recall them straightaway. In addition we tested verbal intelligence (EPVT).

At the end of the project (as well as at other times) we gave the children standardized tests of reading and spelling, and we also tested their IQ (WISC/R) to exclude the effects of intellectual differences. To check that our results were specific to reading and spelling and not to educational achievement in general we also included a standardized mathematical test (MATB-NFER), which we administered to 263 of our total sample of 368.

There were high correlations between the initial sound categorization scores and the children's reading and spelling over 3 yr later (Table 3). Stepwise multiple regressions established that these relationships remained strong even when the influence of intellectual level at the time of the initial and the final tests and of differences in memory were removed (Table 3). In every case categorizing sound accounted for a significant proportion of the variance in reading and spelling with these other factors controlled.

So a definite relationship does exist between a child's skill in categorizing sounds and his eventual success in reading and spelling. The design of the project, for the reasons just given, included a training study as a check that any such relationship is a causal one. 65 children were selected from our sample and divided into four groups closely matched for age, verbal intelligence and their original scores on sound categorization. These children were drawn from those with lower scores on sound categorization (at least two standard deviations below the mean); they could not read when the training began. Starting in the second year of the project two of the groups (I and II) received intensive training in categorizing sounds. The training involved 40 individual sessions which were spread over 2 yr.

Table 1 Details of sample

	Children initially tested at age 4 yr	Children initially tested at age 5 yr
N at end of project	104	264
Initial tests		
Mean age (months)	58.62	65.52
Mean EPVT	110.62	109.39
Final tests		
Mean age (months)	101.85	101.42
Mean IQ (WISC)	113.38	106.79
Mean reading age (months		
Schonell	103.13	100.03
Neale	105.13	101.30
Mean spelling age (months)		
Schonell	97.27	93.94

Table 2 Examples of words used in initial sound categorization tests and mean scores on these tests

	4-yr group				5-yr group				
	Words given to children			Mean correct (out of 10)	Words given to children				Mean correct (out of 10)
Sounds in common									
First sound	*hill*	pig	pin	5.69 (1.90)	bud	bun	bus	*rug*	5.36 (2.29)
	bus	bun	*rug*		pip	pin	*hill*	pig	
Middle sound	cot	pot	*hat*	7.53 (1.96)	lot	cot	*hat*	pot	6.89 (2.35)
	pin	bun	gun		fun	*pin*	bun	gun	
End sound	pin	win	*sit*	7.42 (2.09)	pin	win	*sit*	fin	6.67 (2.33)
	doll	hop	top		*doll*	hop	top	pop	

Standard deviations given in parentheses.

With the help of coloured pictures of familiar objects the children were taught that the same word shared common beginning (hen, hat), middle (hen, pet) and end (hen, man) sounds with other words and thus could be categorized in different ways. Group I received this training only, but group II in addition was taught, with the help of plastic letters, how each common sound was represented by a letter of the alphabet (see ref. 2 for further details of this method). The other two groups were controls. Group III was also taught over the same period in as many sessions and with the same pictures how to categorize but here the categories were conceptual ones; the children were taught that the same word could be classified in several different ways (for example, hen, bat (animals); hen, pig (farm animals)). Group IV received no training at all.

The training had a considerable effect which was specific to reading and spelling (Table 4). At the end of the project group I (trained on sound categorization only) was ahead of group III (trained on conceptual categorization only) by 3–4 months in standardized tests of reading and spelling. This suggests a causal relationship between sound categorization and reading and spelling. Group II (trained with alphabetic letters as well as on sound categorization) succeeded even better than group I (trained on sound categorization only) in reading and particularly in spelling. This suggests that training in sound categorization is more effective when it also involves an explicit connection with the alphabet. That the relationship is specific to these two skills is shown by the mathematics results where the differences were a great deal smaller.

Analyses of covariance, in which the covariates were the childrens's final IQ scores and their age at the time of the final reading and spelling tests, established that the group differences were significant in the case of reading (Schonell: $F=5.23$; d.f.3,58; $P<0.003$. Neale: $F=7.80$; d.f.3,58; $P<0.001$) and of spelling ($F=12.18$; d.f.3,58; $P<0.001$)) but not in the case of mathematics ($F=1.64$; d.f.3,39; P, not significant). Post tests (Tukey's HSD) showed that group II was significantly better than both control groups (groups III and IV) in Schonell and in Neale reading ($P<0.05$) and in Schonell spelling ($P<0.01$). There was no significant difference between groups I and II (the two groups trained in sound categorization) in the two reading tests but group II did surpass group I in spelling ($P<0.05$). Although reading and spelling scores in group I were always ahead of those of group III this difference did not reach significance in the post tests. But the consistent 3–4-month superiority of group I over group III does strongly suggest that training in sound categorization affects progress in reading and spelling. Group I was significantly better than group IV (the untrained control group) in the two reading tests and in the spelling test ($P<0.05$). On the other hand there were no significant differences at all between the two control groups (III and IV).

Table 3 Correlations between initial sound categorization and final reading and spelling levels

Correlations between initial scores and final scores

	Initial scores:					
	Sound categorization		EPVT		Memory	
Final scores	4	5	4	5	4	5
Reading: Schonell	0.57	0.44	0.52	0.39	0.40	0.22
Reading: Neale	0.53	0.48	0.52	0.44	0.40	0.25
Spelling: Schonell	0.48	0.44	0.33	0.31	0.33	0.20

Multiple regressions testing relationship of initial sound categorization to final reading and spelling levels

	Schonell reading		Neale reading		Schonell spelling	
	4	5	4	5	4	5
% Of total variance accounted for by all variables	47.98	29.88	47.55	34.52	33.59	24.77
% Of total variance accounted for by sound categorization*	9.84†	4.06†	6.24†	4.56†	8.09†	5.59†

* IQ, EPVT, final CA and memory controlled.
† $P<0.001$.

Table 4 Training study: details of groups and mean final reading, spelling and mathematics levels

		Mean scores			
		Experimental groups		Control groups	
	Groups	I	II	III	IV
	N	13	13	26	13
Aptitude tests					
Initial EPVT		103.00	103.00	102.34	102.69
Final IQ (WISC/R)		97.15	101.23	102.96	100.15
Final educational tests					
Schonell: reading age (months)		92.23	96.96	88.48	84.46
Neale: reading age (months)		93.47	99.77	89.09	85.70
Schonell: spelling age (months)		85.97	98.81	81.76	75.15
	N	9	8	20	7
Maths MATB (ratio score)		91.27	91.09	87.99	84.13

Reading, spelling and mathematics mean scores are adjusted for two covariates: age and IQ.

Put together our longitudinal and training results provide strong support for the hypothesis that the awareness of rhyme and alliteration which children acquire before they go to school, possibly as a result of their experiences at home, has a powerful influence on their eventual success in learning to read and to spell. Although others have suggested a link between phono logical awareness and reading[3-5] our study is the first adequate empirical evidence that the link is causal. Our results also show how specific experiences which a child has before he goes to school may affect his progress once he gets there.

We thank Morag Maclean for help with gathering and analysing the data, the Oxford Education Authority and and the schools for their cooperation, and the SSRC for supporting our research.

Received 13 September; accepted 17 November 1982.

1. Bradley, L. & Bryant, P. E. *Nature* **271**, 746–747 (1978).
2. Bradley, L. *Assessing Reading Difficulties* (Macmillan, London, 1980).
3. Goldstein, D. M. *J. educ. Psychol.* **68**, 680–688 (1976).
4. Liberman, I. *et al.* in *Toward a Psychology of Reading* (eds Reber, A. & Scarborough, D.) (L. Erlbaum Association, Hillsdale, New Jersey, 1977).
5. Lunderg, I., Olofsson, A. & Wall, S., *Scand. J. Psychol.* **21**, 159–173 (1980).

Chloride impermeability in cystic fibrosis

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Cystic fibrosis is the most common fatal genetic disease affecting caucasians and is perhaps best characterized as an exocrinopathy involving a disturbance in fluid and electrolyte transport[1]. A high NaCl concentration in the sweat is characteristic of patients with this disease; the basic physiological reason for this abnormality is unknown. We have microperfused isolated sweat ducts from control subjects and cystic fibrosis patients, and report here results which suggest that abnormally low Cl^- permeability in cystic fibrosis leads to poor reabsorption of NaCl in the sweat duct, and hence to a high concentration of NaCl in the sweat.

Sweat glands were microdissected from skin biopsies taken from five control subjects and three cystic fibrosis patients. All subjects were males between 23 and 28 yr old. Single sweat glands were dissected further to isolate the reabsorptive duct from the secretory coil. One end of the reabsorptive duct was then cannulated with a micropipette[2] which also served as a microelectrode in the lumen of the duct. To avoid significant changes in the composition of the perfusion fluids due to reabsorptive activity, duct lengths of 1.5–2.0 mm were perfused at rates $>100\ \mathrm{nl\ min^{-1}}$ at 25 °C. The bathing solution always contained 150 mM NaCl while the duct was perfused with solutions of different composition (see Table 1). Transepithelial potential differences during perfusions were recorded via saturated KCl bridges connecting the bathing solution and the perfusion micropipette to a high impedance electrometer (Kiethley 610C) using Ag-Ag/Cl electrodes. Asymmetries without the duct in place were usually $< \pm 1.0$ mV and were subtracted from all measurements.

During periods of perfusion in which there were identical concentrations (150 mM) of NaCl in the bath and in the lumen, the average spontaneous potential in control ducts was −6.8 mV, with the lumen negative with respect to the bath, while in the same conditions the average potential in ducts from cystic fibrosis patients was −76.9. This markedly increased negative potential in the cystic fibrosis duct cannot be due to increased Na^+ transport as suggested for cystic fibrosis respiratory tissues[3], as ductal reabsorption of Na^+ is only about one-third to one-fifth of that in normal glands[4,5]. It therefore seems likely that the elevated potential is due to a separation of charge brought about by a difference in the permeability of anions in the two tissues. To test this possibility, a 1 : 3 dilution diffusion potential for NaCl (dilute solution in the lumen) and a bi-ionic diffusion potential for Na_2SO_4 (lumen) and NaCl (bath) were measured before and after inhibiting electrolyte transport with ouabain. In control ducts, the potential in the lumen before ouabain rose to −24.2 mV when the perfusate was 50 mM NaCl, indicating that Cl^- is more permeable than Na^+ in control ducts. Changing the perfusate to Na_2SO_4 in which the SO_4 anion is assumed to be relatively impermeable, caused the potential to increase further to −75.5 mV, which is almost identical to the potential observed in cystic fibrosis ducts perfused with 150 mM NaCl (Table 1). This result argues strongly that the mechanisms for active Na^+ reabsorption in the cystic fibrosis ducts are not impaired and that Cl^- passively follows Na^+ out of the normal duct. In the cystic fibrosis duct, the luminal potential fell to −47.6 mV with 50 mM NaCl as the perfusate and to −33.3 mV with Na_2SO_4 as the perfusate (Table 1). The drop in the potential with lower concentrations of NaCl in the lumen may be due to some extent to the diffusion potential contribution, but the reason for the decrease during perfusion with Na_2SO_4 is not clear. As the potential in one duct did not fall during this perfusion, the decrease may be related to a variable, time-related reduction in tissue activity *in vitro*.

Table 1 Average luminal potential differences in cystic fibrosis and normal sweat ducts perfused with solutions of varying composition

	150 mM NaCl	50 mM NaCl	75 mM Na_2SO_4
Pre-ouabain			
control (n = 7)	−6.8 ± 2.5	−24.2 ± 2.4	−75.5 ± 11.1
CF (n = 5)	−76.9 ± 13.2*	−47.6 ± 12.3†	−33.3 ± 19.5
Post-ouabain			
control (n = 7)	−0.9 ± 0.5	−14.8 ± 1.3	−42.3 ± 6.5
CF (n = 5)	−0.9 ± 1.7	+9.9 ± 3.8*	−4.4 ± 1.7†

Values shown are the average luminal potential differences in sweat ducts microperfused with solutions of different composition before and after exposing the contraluminal surface of the duct to 5×10^{-6} M ouabain. In addition to the principal solute indicated, all solutions contained: 2.5 mM KCl, 2.5 mM NaH_2PO_4, 1.0 mM $CaCl_2$, 1.0 mM $MgSO_4$ and 10.0 mM glucose. Sufficient mannitol was added to hypotonic solutions to make all solutions iso-osmotic with plasma. More than one sweat duct from two of the control and two of the cystic (CF) subjects were microperfused so that the results represent the mean ± s.e.m. of seven control sweat ducts and five cystic fibrosis sweat ducts. Significant differences were tested by Student's t-test.
*$P < 0.001$; † $P < 0.05$.

Treating the serosal side of the tissue with ouabain virtually abolished the spontaneous potential difference (Table 1). Nonetheless, the average dilution diffusion potential in control ducts was −14.8 mV, but in cystic fibrosis ducts the polarity of the potential was reversed with an average value of +9.9 mV. The change in sign for cystic fibrosis ducts in the absence of active transport, clearly demonstrates that the passive permeability properties of the epithelium are significantly different and reversed compared with normal ducts. Using the 'constant-field equation' (refs 6, 7) to solve for the ratio of the Na^+ permeability to the Cl^- permeability (P_{Na}/P_{Cl}) from the potentials generated in each tissue, we found that P_{Na}/P_{Cl} for controls was 0.26 while for cystic fibrosis patients it was 2.3. Thus the Cl^- permeability in control ducts is almost an order of magnitude higher than in cystic fibrosis ducts. This calculated difference may be significantly underestimated as measured potentials may be less

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