

# Substitution Errors in a Computer Model of Early Reading

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## Abstract

A computer model of early word recognition has been built that uses only visual cues to recognise words, broadly following Seymour's view of reading development (Seymour et al., 1989; Cassidy, 1990a). Written words are represented as a partial ordering on a set of letter instances. This allows various degrees of positional information to be recorded, from none at all to a complete ordering of all the letters in the word. In addition, some letters may not be identified, their place being marked by a symbol representing, for instance, any ascender, any letter or any group of letters.

The model is exposed to examples of first year reading material collected from local schools. As it 'reads' it adds new words to its lexicon. The performance of the model can be monitored as the lexicon grows and a corpus of substitution errors (where an incorrect word is substituted for a target) can be collected.

This paper describes a number of experiments performed using the model to explore the development of visual word recognition. Parts of the recognition procedure are varied and the results are compared to those observed in young children at various stages of development.

## 1 Introduction

Ethan is a computer model of reading development. This paper describes some experiments done using Ethan to explore the very first stages of the development of word recognition skills. The primary goal in building Ethan is to provide a feasible developmental model: one where each stage<sup>1</sup> follows from the one before and where the transitions are feasible given the child's knowledge and learning environment.

Seymour, Evans and Kinnison (1989) propose a model of reading development in which the child starts to read using a purely visual recognition strategy. Words are recognised based on their visual form (eg. as a sequence of letters); no use is made of the relationship between orthography and phonology. From a developmental point of view this makes sense, since the pre-reader can be expected to have knowledge of visual forms (to be able to identify shapes and objects) which can be brought to bear on the problem of word recognition. An alternative view (Stuart and Coltheart, 1988) suggest that if a pre-reader has sufficient knowledge of phonology, the purely visual stage is not necessary, and the child can begin to read using a phonological strategy. Even if this is the case, the child must still have acquired knowledge about the nature of print from somewhere; there is still room for the use of a visual strategy, be it very short or even in parallel with another strategy. Using a visual strategy provides the child with the opportunity to learn more about the visual form of words and, since it is one way of pronouncing print, about the relationship between print and sound.

Ethan could be seen as a competitor to Seidenberg and McClelland's (1990) connectionist model of word recognition, which they describe as a developmental model (but see (Casidy, 1990b)). The motivation behind that model was to reproduce quantitative measures of reading behaviour, in particular lexical decision times and word naming latencies. As a 'side effect', Seidenberg and McClelland note that the performance of the model at various points in its training is similar to that of developing readers. However they do not attempt to explain how children learn the things they do from the data (reading material) they have available, or how the model that they present arises from a previous state of knowledge. Ethan is an attempt to do just these things. Ethan is not a connectionist model, because its author believes that current connectionist algorithms are not ready for the task of cognitive modelling, and that given this, a symbolic account of reading development will be more informative.

## 2 Lexical Representations

In English orthography, a word token is written as a sequence of letters, ordered from left to right. In order to recognise a token as an English word, the reader must store a representation of it; this could be as a procedure for recognising the token, as a pattern to match against it, or as a set of weights in a network that will respond to it. Whatever form the representation takes, there is certain information that it must capture about

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<sup>1</sup>Where a stage is just a part of the development of a child and does not necessarily correspond to one of the stages proposed by, for example (Frith, 1985)

the make-up of the word token. Some of the requirements for this representation can be gleaned from observations of children's word recognition successes and failures.

Perhaps the least controversial aspect of the representation is that it must record which letters are contained in the word token. This is not as simple as it may seem however; for example, the word *cabbage* contains the letters  $[a, b, c, e, g]$  – we need to record the fact that there are two distinct *a*'s and two distinct *b*'s. In fact we need to record the *letter tokens* in the word token; in Ethan these are called *letter instances*.

Observations of children's word recognition errors show that at least in the early stages of development, they do not take notice of all of the letters in a word. Errors often share only the first or last letter with the target and occasionally have only a salient feature such as a *t* or a *g* in common (Stuart and Coltheart, 1988; Campbell, 1987). This implies either that the representation of the word token only contains these salient features or that the procedure that recognises word tokens is willing to ignore much of what is stored in order to produce a response. Evidence from children's spelling (Gentry, 1982) suggests that, if children use the same lexical representation for reading and spelling, it is the representation that lacks detail; for instance, a child might produce a spelling *ct* for *cat*.

The ordering of the letter instances in a word token is another aspect of its structure that should be recorded in a representation. In fact, children do not always pay attention to letter order or position, and so produce errors like *pot* for *top* and *black* for *likes* (Seymour and Elder, 1986). Again, there is a choice between a procedure that ignores letter order or position when doing word recognition or a representation where this is not even recorded. In the second case though, the representation must be capable of recording ordering, since the mature reader will surely use this information.

Ethan's representation of a word token consists of a partial ordering on a set of letter instances. In a partial ordering, the relative order of some pairs of elements in the set are specified, other orderings can be left unspecified. It is therefore possible to record anything from an unordered set of letters to a totally ordered sequence. For example, the partial order  $[a \rightarrow b, c, a \rightarrow d]$  says that both *b* and *d* come after *a*, but the relative positions of *b*, *c* and *d* are not specified. As well as letter instances, the representation of a word token can contain markers for, say, ascenders or descenders. This allows Ethan to record an imprecise description of a word token in the case where the corresponding letters are not salient or when they have not yet been learned consistently. A partial order on a set of letter instances is referred to as a partial sequence in the rest of this paper.

The model of word recognition presented here is one where a representation of a word token is matched against stored representations of known words in order to decide on the identity of the token. To do this, it is necessary to propose a method of finding those lexical items that are likely to match against a target token. Ethan's lexicon contains a partial sequence representation for each word it knows how to read. The lexical items are organised into buckets, each bucket being labelled by a key; the key is some salient feature of the word, for instance the first or last letter. Given a key, it is possible to gain access to all of the lexical items stored under that key very quickly (in constant time).

### 3 How Ethan Reads

Ethan recognises words by comparing a representation of the word token with similar stored representations until a match is found. This process is made more efficient by the way in which the lexicon is organised. This section describes each of the processes in figure 1. In each case there are a number of variations on the central theme; the purpose of this paper is to explore these variations<sup>2</sup>.

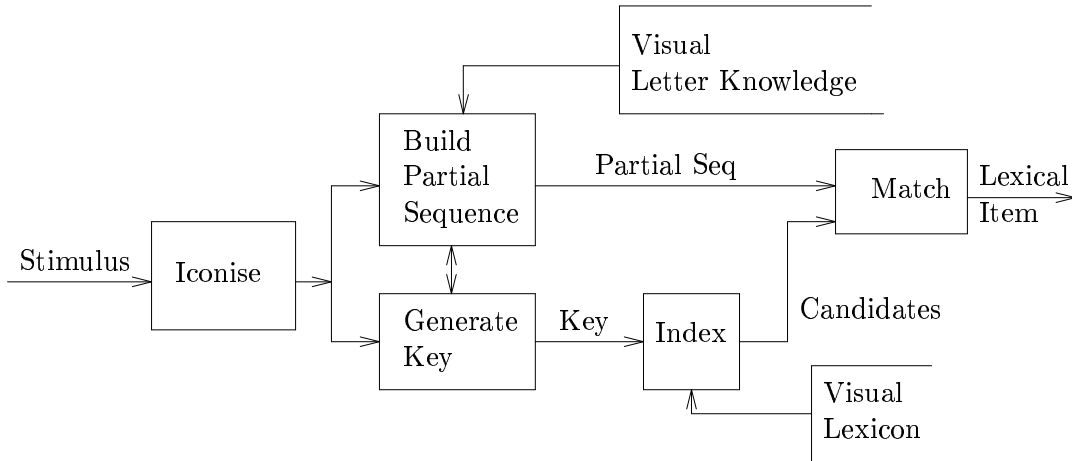


Figure 1: The model of word recognition implemented in Ethan<sup>3</sup>

A description of the word token is built up from the raw stimulus by the `ICONISE` procedure. The iconic description delineates a set of icons and their relative spatial position. These icons are not identified as letter tokens at this stage. Ethan simulates this process by taking a string of letters as input and producing a string of icons as output. The icons correspond to either single letters or groups of letters. It is possible for the `ICONISE` procedure to fail to represent some letters; this corresponds to the child not paying attention to those letters at all (for instance the middle letters in a word, if they are not salient for some reason).

From the iconic description, the `BUILD PARTIAL SEQUENCE` procedure identifies the icons as instances of letters and constructs a partial sequence representation of the word token. The ordering imposed on the elements of the partial sequence reflects the spatial ordering of the icons. However, information as to the exact spatial relationships (left-of, above etc.) is not preserved (see (Seymour, 1979) for a discussion of early visual processing of written words). The degree of ordering recorded depends on the child's knowledge of the need for ordering in word representation, for instance the child may only pay attention to the relative ordering of the boundary letters.

The `BUILD PARTIAL SEQUENCE` procedure uses knowledge of the visual forms of letters to

<sup>2</sup>For more details on these and other aspects of this model see (Cassidy, 1990a).

<sup>3</sup>This diagram should be interpreted as a dataflow diagram. The boxes represent processes, the arrows represent flow of information and are labeled with the data that flows along them, the open sided boxes represent data stores.

build a description of a word token as a set of letter instances. It is important to note that knowing a letter identity for this purpose is not the same as being able to name or give a sound for a letter. All that is required is that the child be able to consistently differentiate a given letter from all other graphic forms, and give it a unique label; the label doesn't have to correspond to a letter name, although at some point in the child's development, this association will be learned. Given this, Ethan is assumed to know nearly all the letters at an early stage in its development. As shown in figure 2, the visual forms (allographs) are organised into a classification hierarchy. Ethan distinguishes upper and lower case forms of letters.

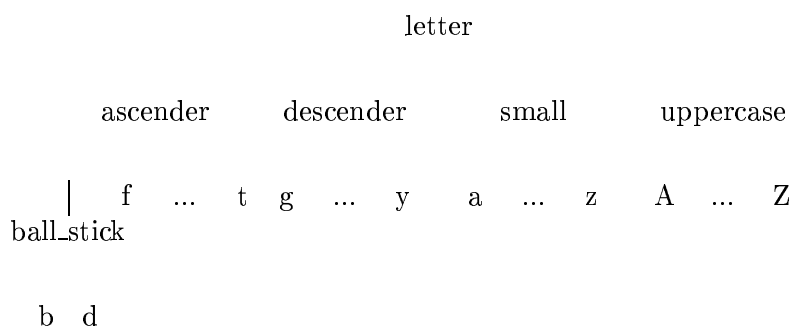


Figure 2: Letter knowledge is organised as a classification hierarchy.

To find a set of candidate lexical entries to match this word token against, a key is needed; this key will identify one of the buckets within the lexicon where the representation of this word should be stored, if it is known to the reader. Clearly, the same key should be selected each time a word is seen; I suggest that learning which features of a word token should be used as keys is an important part of the development of visual word recognition. The method of selecting a key will have an impact on the nature of any errors produced. For instance, if the child always chooses the first letter as a key, then any error will always share the first letter with the target, since only the lexical items in that bucket are examined.

All of the lexical items in the appropriate bucket are retrieved and are compared with the representation of the target word token; that is, a linear search is done within the appropriate bucket. If the items in each bucket are ordered on recency of access, this linear search can give rise to both a recency and a frequency effect (Forster, 1976).

Ethan adds the representation of a word token into the lexicon if it has not been seen before. In the current implementation, new words are added only when Ethan fails to make a response to a word token. If either a correct or an error response is made, no action is taken<sup>4</sup>. The representation of the word token is added to the appropriate bucket in the lexicon and becomes the lexical entry for that word. Note that if the procedure for selecting keys is not consistent, this strategy can result in some words having more than one lexical entry – in different buckets.

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<sup>4</sup>This strategy does not necessarily correspond to a real learning situation; it is a first approximation to a strategy for extending the lexicon. The implications of alternative strategies will be explored at a later date.

## 4 Building a Visual Lexicon

These experiments look at Ethan’s performance in building a small lexicon, corresponding to what might be the child’s first two months of school experience in reading. Ethan is exposed to a number of stories (taken from a corpus of books used in NZ schools) and builds a visual lexicon as it reads. The error performance and the size and nature of the lexicon can be monitored as the experiment progresses.

As has been indicated, there are a number of parameters in the model that affect the way that a word token is represented. In these experiments, various combinations of these parameters are tested by allowing Ethan to read the same set of stories using each combination. The results will then be compared with each other and with observations from the literature to evaluate each combination. The parameters that are varied are:

**Icons:** The `ICONISE` procedure produces an iconic description of the word token. It is possible for this procedure to miss out some letters; the variations concern what happens when letters are missed:

- **OMIT:** Boundary letters and salient internal letters (for instance, an isolated ascender or descender) are retained, everything else is omitted.
- **GROUPS:** Boundary and salient internal letters are identified perfectly, groups of non-salient internal letters are replaced by a group marker.
- **MARKERS:** Similar to `GROUPS` but most (not all) non-salient internal letters are replaced by a marker showing the class of the letter (eg. ascender).
- **EVERYTHING:** All letters are retained.

**Ordering:** The `BUILD PARTIAL SEQUENCE` procedure identifies the icons as letters and records their ordering. The variations concern the degree of ordering recorded:

- **NONE:** No order is recorded
- **LETTERS:** Everything but group markers are ordered relative to the boundary letters. This option only makes sense with the *group* `ICONISE` procedure.
- **BOUNDARY:** Everything is ordered relative to the boundary letters.

**Key:** The `GENERATE KEY:` procedure chooses some feature of the word token to use as a key for selecting the appropriate bucket from the lexicon. In the current experiments there are only two versions:

- **RANDOM:** A random letter is selected from those included in the iconised version of the word token.
- **FIRST/LAST:** either the first or last letter of the word token is used.

The experiments use a number of combinations of these variations, as shown in table 1. In each experiment Ethan read a number of stories from the Emergent Level corpus<sup>5</sup>.

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<sup>5</sup>Emergent Level (also known as Magenta) is the first category in the Ready to Read series of books used in NZ schools. The corpus includes these and other books at this level of difficulty which are used for a child’s first introduction to reading in school.

EXPT	ICON	ORDERING	KEY
1	GROUPS	NONE	RANDOM
2	OMIT	NONE	RANDOM
3	MARKERS	NONE	RANDOM
4	GROUPS	LETTERS	RANDOM
5	GROUPS	BOUNDRY	RANDOM
6	OMIT	BOUNDRY	RANDOM
7	MARKERS	BOUNDRY	RANDOM
8	EVERYTHING	BOUNDRY	FIRST/LAST

Table 1: Parameters for the experiments.

Experiments 1–3 used ten stories from this set, all of the others used twenty stories. Some example stories are shown in appendix A. Each story is read twice. After the second reading a report is printed showing the substitutions made and statistics on Ethan’s performance (on the first reading, most of the words are not in Ethan’s lexicon and so its performance is poor).

#### 4.1 Results and Discussion

EXPT	CORRECT(%)	ERROR(%)	REFUSAL(%)	TARGET/ ERROR LENGTH	LEXICAL ENTRIES
1	40	57	3	0.05	1.33
2	76	11	13	0.66	1.55
3	68	10	22	0.71	1.79
4	47	49	4	0.20	1.25
5	74	15	11	0.38	1.49
6	76	13	11	0.39	1.60
7	72	6	22	0.54	2.09
8	89	0	11	1.00	1.61

Table 2: Results of the simulation experiments with Ethan.

Table 2 presents the results of the simulation experiments. The performance of the model in most of the experiments is reasonable; Ethan gets about 70% of the words correct, makes 10-15% substitutions and fails to respond to 15-20% of words. This compares favourably with results presented by Seymour and Elder (1986), shown in table 3, of children reading familiar words; except perhaps that Ethan is less likely to make a refusal than Seymour’s subjects. Seymour found that when reading unfamiliar words (those words not already in the reading vocabulary), children made many more refusals. In these experiments Ethan is exposed to each story twice and statistics are collected for the second exposure. In a sense then, Ethan is tested on familiar words, having had a chance to add them to its lexicon. If we look at Ethan’s performance on its first exposure to each story, we see an increase in the number of refusals (for example in Experiment 2, Ethan makes 42%

refusals and 11% errors). It is clear why this happens – the words are not present in Ethan’s lexicon and so cannot be recognised.

	FAMILIAR			UNFAMILIAR		
	CORRECT(%)	ERROR(%)	REFUSAL(%)	CORRECT(%)	ERROR(%)	REFUSAL(%)
KN	79	4	18	7	6	88
CR	72	8	20	1	8	90
NW	63	20	17	3	24	74
DR	38	14	48	2	18	81

Table 3: Error performance of four beginning readers (taken from (Seymour and Elder, 1986)).

Table 2 shows the correlation between the length of the target and the length of the response for the substitution errors made in each experiment. Seymour (Seymour and Elder, 1986) suggests that this correlation indicates that children use length as a cue in early reading; he observes correlations as high as 0.9 in first year readers. The representation of word tokens used here does not include the length explicitly – long words are not differentiated from short words. One aim of these simulations was to show that these length effects could be reproduced without an explicit record of length. The experiments do show a significant length correlation, in particular in experiments 2, 3 and 7. It is perhaps surprising that this effect occurs in experiment 2 since the ICONISE procedure used omits most of the letters in the word. The length correlation is low for all of the experiments using group icons. The original intention of introducing group icons into the representation was to try to preserve information about length; it seems to have had the opposite effect. The reason is that since the size of a group is indeterminate (from one to four letters), a word token containing a group icon can match another word of very different length. For example [ $t \rightarrow group, group \rightarrow e$ ] (*table*) would match [ $t \rightarrow h, h \rightarrow e$ ] (*the*).

‘Lexical entries’ (table 2) is a measure of the efficiency of lexical storage – the final number of lexical items stored divided by the number of types (distinct words) in the lexicon. For a good reader, this ratio ought to be one, so that any word has just one representation in the lexicon. As has been mentioned before, Ethan may store a word a number of times if the key selection procedure is not consistent, which is the case with the random procedure used in most of the experiments. The table shows that most of the experiments produced more than one lexical representation on average.

Although no ordering is represented in the early experiments, the substitutions made still show a preponderance of errors sharing either the first or last letters. This is a result of the assumption about the ICONISE procedure – that it encodes visually distinct letters, such as boundary letters and isolated ascenders or descenders. This assumption means that Ethan is very likely to notice the boundary letters in a word (and record them in a representation of the word token) and therefore any errors will tend to share these letters with the target. The use of a key selection procedure that chooses a random letter means that most words will be stored at least twice – under both the first and last letters and,



to a lesser extent, any salient internal letters.

Turning now to an evaluation of the individual experiments, it is clear that some of the simulations produced more realistic results than others. As has been mentioned, all of the experiments with the *group* ICONISE procedure produced very poor target/error length correlations because groups are able to match an indeterminate number of letters. Groups also result in a large number of errors in the experiments where no ordering is imposed on the groups (1 and 4). In both cases a representation containing a group can match almost any other stored representation (for instance,  $[t, \textit{group}, e]$  (*table*) will match  $[s, \textit{group}, p]$  (*stop*) – the *group* in *table* matches the *s* and *p* in *stop*, and the *group* in *stop* matches the *t* and *e* in *table*). In experiment 5, groups are included in the ordering and the performance improves dramatically over experiment 4 where they were not ordered, although the length correlation is still low. From these results, it can be concluded that group markers, as used in this implementation, do not provide a useful part of a token representation.

Experiments 2 and 3 give very similar quantitative performance, and the best target/error correlation of all. Experiment 3 produced a larger proportion of refusals and fewer correct responses. This happens because the marker ICONISE procedure inserts some markers (eg. ascender) into the representation of a token but is not consistent in which markers it inserts. On one occasion the representation of *table* might be  $[t, \textit{ascender}, e]$  and on another  $[t, \textit{ascender}, \textit{ascender}, e]$ ; since these two representations do not match, Ethan will make a refusal or an error response. On the other hand, in experiment 2, the ICONISE procedure is more consistent in building representations of word tokens. This is reflected in the relative sizes of the lexicons in the two experiments; experiment 3 has more duplication in its lexicon due to storing different representations of the same word.

When ordering is imposed on the representation the error performance is similar to the unordered case. In experiments 5 and 6 however, there is a dramatic drop in the target/error length correlation; this seems, in part, to be a result of the increased vocabulary size (these experiments were run on 20 stories whereas the earlier experiments used only 10). When there are more lexical candidates available to match, it is more likely that a matching candidate will be found whose length is different to the target. If the representation were to fully encode the length of the target, this effect would not occur and the length correlation would be perfect (this can be seen in experiment 8 where all letters are included in the representation). Experiment 7 has the best length correlation of the ordered cases, the inclusion of markers in the word representation means that fewer letters are missed out and so the length of the word is encoded more fully.

Experiment 8 shows that this word recognition procedure is capable of near perfect operation. This is not surprising and, since the performance is so good, it is not a realistic model of children's reading behaviour.

It is informative to look at the errors that were produced by Ethan in the experiments: table 4 gives some example errors from experiments 2,3,6 and 7. The table shows errors made in a particular experiment that were not repeated in any other experiment. A common feature of the errors is that target and response share at least one salient letter, often a boundary. In the later experiments, they tend to share either first or last letter; this is because of the ordering imposed on the representation precludes a match between

a first letter and a last letter:  $[p \rightarrow o, o \rightarrow t]$  will not match  $[t \rightarrow o, o \rightarrow p]$ . Another consequence of the ordering, and the fact that the identities of both boundaries tend to be recorded, is that the error will share both first and last letters with the target.

An important comment on the errors is that they are not very realistic, in that on many occasions Ethan responds with a low frequency word (tree) when presented with a high frequency target (this). This stems, in part, from the deficiencies of Ethan’s model of memory; Ethan has perfect recall, if it decides to remember something. A more realistic model might forget words that are not accessed for some time. However, there are a number of other factors, such as conscious filtering of error responses, that Ethan does not model that can influence the nature of the errors produced. It is reassuring to note that children do make errors like Ethan’s; Stuart (Stuart, 1989) lists a number of obscure substitutions: and/here, said/ship, for/fish, came/comic etc.

Experiment 2	Experiment 3	Experiment 6	Experiment 7
butterfly/birthday	chairs/chair	bed/fixed	Miss/Me
caterpillar/tunnel	comes/came	bike/broke	sun/see
fly/bumpy	comes/sun	builder/door	then/tree
for/roll	hole/laugh	drive/beetle	this/tree
lunch/crash	house/blue	thunder/tiger	time/tree
lunch/elephant	house/crash	tree/to	tree/table
table/plate	plum/pole		tree/tunnel
thunder/roll	ride/rainbow		went/want
	run/rainbow		
	swim/comes		
	tree/net		

Table 4: Substitution errors produced by Ethan in some of the simulations (target/response).

## 5 Evaluation

The results suggest that Ethan captures some aspects a child’s first attempts at recognising words using only visual cues. Ethan does not model all of the first year of reading; other mechanisms come in to play, including some use of phonological information. The important question for this project concerns the way the visual lexicon described here serves as a starting point for building a more mature lexicon incorporating larger orthographic structures (morphemes) and phonological information. It is beyond the scope of this paper to provide this full evaluation, however some observations can be made on Ethan’s performance as a visual reader.

Ethan’s performance varies over time. More often than not, it degrades as more words are added to the lexicon: more errors are made and the errors become less believable. Figure 3 shows the change in performance, and in particular, the fall off in the length correlation

(cumulative) with the number of stories read. This degradation arises in part because

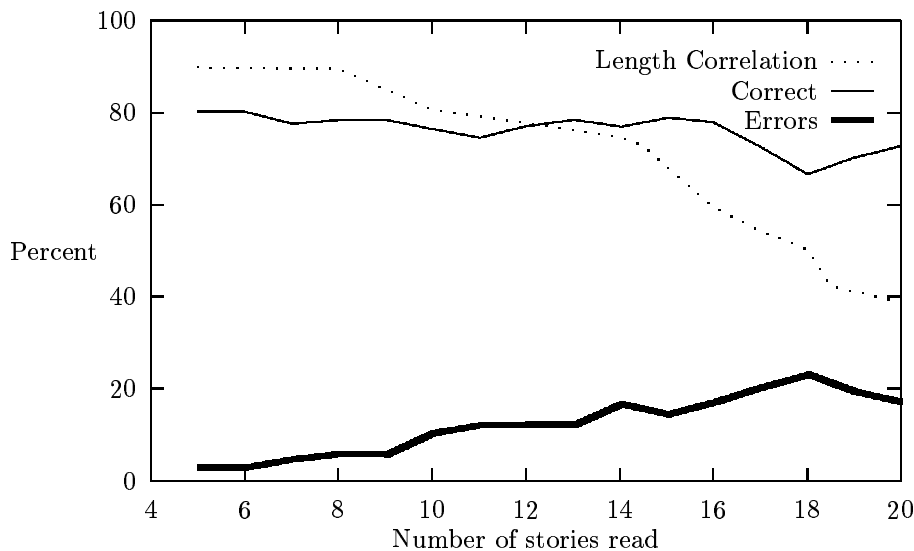


Figure 3: Correct and Error (substitution) responses and length correlation (as a percentage) vs. stories read in Experiment 6

Ethan isn't yet a learning model; new words can be added to the lexicon but Ethan never makes any generalisations from them and never changes the way the lexicon is organised. The different versions of Ethan used in the experiments show that the performance of the model can be improved by changes to parts of the model; for instance, when ordering is introduced into the representation, errors tend to share both initial and final letters with the target. If a more consistent key generation procedure were provided, lexical storage could be made more efficient and the whole recognition procedure should produce fewer errors. Ethan could feasibly learn all of these things and so might advance through the stages used in these experiments to become a better visual reader.

One concern with a learning model is that the representations used in the later stages must be derivable from those of the early stages. This means that they must use the same language, which is why Ethan uses the language of partial orderings: to be able to express word token representations both with and without ordering information. The issue of how the lexicon changes must also be addressed. If Ethan suddenly learns a new, better way of encoding words, and uses it to encode a word to be read, this new representation must be compatible with what is stored in the lexicon. One way to achieve this is to re-write the lexicon each time you decide on an improvement to your representation. This may not be possible in some cases, the information (about ordering, say) is not present in the old version. Another way is to make the new representation compatible with the old, so that the new version will still match with the stored representation – this might be possible if the changes are small.

In conclusion, these experiments have shown that Ethan can reproduce some qualitative

measure of performance of a beginning reader. However, the strategy that Ethan uses at present is not able to model very much of the child's first year; Ethan needs to learn in order to enable its lexicon to grow. Some of this learning can go on within the framework of visual reading, but another strategy must be developed to supplement it. Ethan is ready to do this learning: the representation language used in the lexicon is flexible and able to cope with a richer lexicon. The next stage in this project will concentrate on modelling a phonological route to augment the visual route. It will then look at how Ethan can build a better word recognition procedure from the building blocks of visual and phonological lexicons.

## A The Stories

This section contains some example stories from the magenta level that were used to train Ethan.

**The big hill.** We climb up. We run down. We fall. We roll. We crash. We laugh. Then we climb up again.

**What's for lunch?** "What's for lunch?" said the bird. "Not snail," said the snail. "Not caterpillar," said the caterpillar. "Not beetle," said the beetle. "Not spider," said the spider. "Not butterfly," said the butterfly. "Juicy plum," said the bird.

**I want an icecream.** I want an icecream. I cry. I stamp. I thump. I kick. I smash. I yell. No icecream.

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