PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Biological Constraints on Orthographic Representation

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Biological constraints on orthographic representation

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This paper sets out five constraints that a psychologically efficient orthography must meet. The first four principles are that (1) the elements of the orthography must be easy to discriminate; (2) it must be possible to write the code quickly, without elaborate technology; (3) the code must permit unambiguous, fast and fail-safe access to the meanings of messages; (4) the system as a whole should be learnable without undue expenditure of time and effort. A fifth principle, that the dimensions of formal and semantic similarity in an orthography should be orthogonal, is argued to be the best way of ensuring that reading errors are kept to a minimum. Evidence for the last principle is derived from the study of errors made by subjects with acquired dyslexia.

1. Introduction

Voltaire once remarked that writing systems are paintings of the human voice: a neat metaphor that immediately provokes the question, 'In what style should these paintings be?' Cubist (as in Sumerian cuneiform)? Abstractionist (as in early Phoenician)? Hard-edge realist (as in Egyptian hieroglyphic)? Voltaire's own answer was that the more closely writing resembles speech the better it is. But this answer is unhelpful in the absence of any explanation of the dimensions of resemblance that are in question when language is to be transcoded between the auditory and visual modality. Perhaps, then, we should stand back a little from the problem and ask, 'What are the critical design features of an orthography?' What are the psychological, linguistic and biological principles within which 'natural' orthographies have evolved? There are four very obvious constraints to which an effective orthography must conform.

1. The code-elements and combinations thereof must be reasonably easy to discriminate from each other.
2. One must be able to write the code fairly quickly (without having available a technology more complex than pen or pencil).
3. The code should give relatively unambiguous, fast and fail-safe access to the meaning of the message.
4. The system as a whole should not be impossibly difficult to learn.

We thus have two constraints that relate to the 'physical' nature of the signal (and the input and output softwares that deal with signal reception and generation); one *linguistic* constraint that relates to the form of the mapping between physical signals and the language they express; and finally one general 'systemic' constraint relating to the time at the learner's disposal. The Cherokee Indians were delighted with the development of their syllabary, and claimed that they could learn the new writing system in one day compared with the 4 years it took them to learn to write Cherokee in the English alphabet. Perhaps the Indians would have appreciated English orthography more had they tried to write Cherokee in Chinese logography, a system for which scholars assure us one needs a lifetime to acquire a decent reading vocabulary.

All writing systems must make compromises between their components, for it is clear that the principles I have outlined will often pull in different directions. In particular, the requirements of legibility in reception and relatively effortless speed of production are orthogonal. Thus early monumental writing systems (hieroglyphic, for example), in which the signs are highly distinct when carved into the rock face, eventually developed a visually sloppier linear cursive form when speed of writing became important, as in correspondence or business. To pick an example slightly closer to home, Wing (1979) has shown that although one can, of course, read other people's block capital handwriting rather faster than one can read their cursive, this is bought at the cost of block capitals being some 50% slower to write than cursive. Wing (1979) concludes that 'the advantage to block capitals in reading is less than their elevation of writing time'. As a motor skill, the production of standard cursive handwritings appears to have a remarkably simple underlying mechanism. The fundamental structure is an oscillatory pattern generated by two joints, one vertical (the fingers) and one horizontal (the wrist). Letter-shapes then emerge from the oscillation train by modulations of acceleration and deceleration that give rise to three basic types of corner: the loop, the cusp, and the arch. Hollerbach (1979) has devised an elegant robot system that provides an excellent simulation of cursive handwriting with the small set of variables just described. The robot fails to dot its i's and cross its t's, but otherwise performs most creditably.

Although the biological mechanism modelled by Hollerbach's theory appears to be a simple one, it is peculiarly liable to disruption. Chédru & Geschwind (1972) have noted that an impairment of writing is 'the most constant and the most striking linguistic disorder' seen in patients in acute confusional states. More pointedly, Leischner (1969) has drawn attention to the frequency with which aphasic patients in the acute phase will write in block capitals and only begin to use cursive script during the course of recovery. Yet in other forms of pathology, the basic structure of cursive script may be retained despite severe motor deficit. For example, in patients with cerebellar disease, a severe impairment of fine motor control may be apparent in the tremor of the handwriting, whereas the overall form of cursive is well preserved. I think we can conclude that the cursive scripts (or running hands) we write today constitute reasonably well adapted solutions to the design problem for orthographies considered purely as visuo-spatial objects, despite their apparent neuronal fragility when cortical damage is involved. Clearly, however, it would be perverse to think of orthographies merely as abstract patterns or uninterpreted visuo-spatial calculi.

2. Reading by ear

How, then, are orthographies interpreted? What kinds of processes mediate between the physical signal and the language it expresses? Children typically learn to read and write after they have mastered the essentials of a spoken language. It accordingly makes sense to think of a writing system as an interface between visuo-motor skills and the neuronal representation of the *auditory* form of a language. Hughlings Jackson echoed Aristotle in seeing written words as 'symbols of symbols' and many other early neurologists believed that writing could only make contact with language via speech. For the nineteenth-century physicians, reading is first sight, then sound, then sense; and writing is first sense, then sound, then graphic action. In the classical diagram of Ludwig Lichtheim (1885), the only path from the 'optic centre' to the 'concept centre' is via the centre for auditory images in the left temporal

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lobe (Wernicke's area). The model also countenances the possibility of accurate reading aloud in the absence of comprehension.

Lichtheim's theory can be summarized by saying that he believes that the proximate access code in reading for meaning must be 'auditory'. What does Lichtheim mean by 'auditory'? Sometimes he means it quite literally, for he reports on a number of cases where 'The patient can easily understand by the ear when he reads aloud, while silent reading remains senseless' (Lichtheim 1885). Sometimes this reading aloud takes the form of reading words as whole words; in other cases, Lichtheim reports that the patient may *spell* the word, either aloud or *sotto voce*, letter by letter (a possibility allowed by those alphabets that do have letter-names distinct from the phonological values that the letters take). This latter strategy, in which the word is reconstructed from the (internal or external) sound of the letter-names, is fairly rare, and is of course an ergonomically ridiculous way of going from print to meaning. 'Reconstruction time' (and hence reading time) is proportional to word length, measured in letters (Staller *et al.* 1978; Warrington & Shallice 1980). A strategy that results in such slow, painstaking performance cannot be part of the core machinery of reading. None the less, the syndrome of 'spelling dyslexia' or 'letter-by-letter reading' constitutes an important demonstration of the distinction between perception and word-perception; the visual word-form system (Warrington & Shallice 1980) can be severely damaged despite the availability of information (analysed and categorized letter-strings) that is, in principle, sufficient to trigger directly the pronunciation and semantic value of words.

Another possibility that Lichtheim seems to have in mind when he discusses auditory (or, better, phonological) routes for reading is the notion that there could be direct mappings between visual inputs and phonological addresses at the 'whole-word' level, i.e. the word as a unitary visual object could be associated with its pronunciation as a unitary phonological object. Schwartz *et al.* (1980) have reported on a patient who could read aloud both regularly and irregularly spelt English words with excellent accuracy but zero comprehension. This suggests to them that 'The visual word form (visual input logogen) activated in some direct fashion an associated representation in a phonological lexicon (output logogen)'. Evidently, reading aloud in this patient is mediated neither by meaning, nor by that rule-governed procedure that allows unknown regular words and neologisms to be pronounced by any fluent manipulator of an alphabet or syllabary.

Of all the 'abstract auditory' routes, the systems of grapheme–phoneme (or grapheme–syllable) correspondence rules that are instanced (more or less clearly) in alphabets and syllabaries have been the most intensively studied (Coltheart, this symposium). The primary behavioural pathology (surface dyslexia) associated with the use (and misuse) of this route can be illustrated from patient J.C., first reported by Marshall & Newcombe (1973) and Holmes (1973). J.C. sustained a large temporo-parietal lesion when hit by a grenade fragment in 1945 at the age of 20 years. Examined in 1969 (and subsequently re-examined on numerous occasions), J.C. was severely impaired in reading, writing and spelling, despite spontaneous speech that is remarkably fluent and grammatical, and excellent comprehension of the oral language. J.C. can print his address but little else. When reading, he frequently gives the impression of not knowing the language and simply acting as an orthography-to-sound 'translator'. He reads many words by slowly and laboriously 'sounding out' the constituent elements. This 'phonic' strategy is maladaptive in that the well known irregularity of English orthography ensures that the correct phonetic values for graphemes often cannot be assigned letter by letter in a single left–right pass. Compare the phonetic values of *a* in *fan*, *fade*, and *father*, or the values of *g* in *girl* and *gin*. Typical examples where J.C. has selected a phonetic value that is a possible realization of a particular letter, but is erroneous in the specific word he is attempting, are:

disease → 'decease'; *unite* → 'unit';
of → 'off'; *grind* → 'grinned';
guest → 'just'; *lose* → 'loss'.

Consistent with Lichtheim's claim that 'auditory images' constitute the access code for semantic interpretation, J.C. defines (correctly) his own (false) response when asked to give the meaning of the stimulus word. Further evidence for this position comes from J.C.'s interpretation of homophones. J.C. will often read a homophone aloud correctly but assign the wrong meaning to it. Thus *billed* is read correctly and glossed as 'to build up, buildings'. These misinterpretations do not result from the overt (erroneous) response overriding an implicit correct assignment of meaning, because such confusions are equally in evidence when J.C. defines homonyms before reading them aloud (Newcombe & Marshall 1981).

All patients with surface dyslexia so far studied have also manifested disorders of writing and spelling. If the patient can write, albeit erroneously, the qualitative form of the dysgraphia parallels the form of the dyslexia. This can be illustrated from M.S., an intelligent and previously literate young man who sustained a severe closed head injury in 1978 at the age of 19 years. M.S., currently under investigation by Freda Newcombe, is a Citizen's Band radio fan who writes in his pocket book the addresses of the people he talks with. Some typical samples are:

FORIST OV DEN (= Forest of Dean); KOVUNTRE (= Coventry);
HOLEWUD (= Hollywood); KASUL BROMICH (= Castle Bromwich);
WUSTU (= Worcester); BERLINSEU (= Valencia).

There can be little doubt then that writing and (silent) reading can take place 'by ear'. None the less, I wish to suggest that Lichtheim was simply wrong in assuming that *all* reading and writing routes involve some 'abstract auditory' system.

3. Reading for meaning

In 1966, Freda Newcombe and I reported a putative symptom-complex, now called 'deep dyslexia', that provides, we believe, strong evidence for a reading subsystem in which semantic interpretation is not mediated by a phonological code (Marshall & Newcombe 1966). The critical difference between surface dyslexia, as previously illustrated by J.C., and deep dyslexia can be shown from the opening lines of a poem by Gustav Leberwurst (1981):

Kuh! Sie Kuh! Sie kann der...
Wer Du ja Wanduhr?

An interpretation in which this passage means 'Goosey Goosey Gander, where do you wander?' is analogous to surface dyslexia, whereas reading it as 'Cow! You cow! Who do you think you are, you and your clock on the wall?' is analogous to deep dyslexia. In essence, the model of reading that Newcombe and I proposed claimed that sound and sense are computed in parallel from the visual address associated with each known input word (Marshall & Newcombe

1973). Deep dyslexia, we argued, is the condition that arises when the route from sight direct to sound is unavailable (as a consequence of brain damage). Previously literate adult subjects with deep dyslexia produce large numbers of semantic errors when reading aloud individual words without context, time pressure, or stimulus degradation. G.R., the first such patient studied by Newcombe and myself, sustained a deep through-and-through wound in the region of the left Sylvian fissure in 1944 at the age of 20 years. Examples of his errors in reading include:

daughter → 'sister'; *talk* → 'speech';
caution → 'danger'; *thirsty* → 'drink';
fair → 'poor'; *guilty* → 'hangman';
larger → 'big'; *his* → 'she';
kill → 'murder'; *before* → 'and'.

Derivational errors are also in evidence. G.R. will frequently misread an adjective or verb as its related nominal (or vice versa). Examples include:

political → 'politician'; *furnish* → 'furniture';
length → 'long'; *memory* → 'remember'.

Errors also occur in which there is a clear visual (shape) similarity between stimulus and response:

anger → 'angel'; *calm* → 'calf';
bless → 'blush'; *crush* → 'crash'.

Visual errors frequently mediate semantic errors. Examples include:

ambition → 'stretcher' [ambulance]; *fate* → 'temper' [hate];
article → 'painter' [artist]; *flow* → 'wheat' [flour];
cape → 'plum' [grape]; *gallon* → 'hangman' [gallows];
chief → 'cook' [chef]; *settle* → 'cow' [cattle].

Reading performance shows a strong effect of the syntactic class of the stimulus items. Concrete nouns stand the best chance of being read correctly; adjectives, verbs, adverbs and abstract nouns are of intermediate difficulty, and all other classes of words ('function words') are practically impossible for G.R. to read. Non-words that are orthographically legal and perfectly pronounceable (e.g. *dake*) are likewise almost never read correctly by subjects with deep dyslexia. The semantic errors that are such a striking feature of the syndrome also occur when G.R. is writing to dictation:

'boat' → *ship*; 'nephew' → *uncle*;
'glove' → *lace*; 'page' → *read*;
'star' → *moon*; 'den' → *house*;
'bun' → *cake*; 'cake' → *bun*.

This reverse aspect of the syndrome – let us call it 'deep dysgraphia' – disproves another nineteenth-century claim. Carl Wernicke (1874) asserted that writing without the mediation of a phonological code is impossible. There is no 'direct path from the concept formed by sensory images to the motor writing center', he argued.

Whereabouts in the processing system should we locate the impairment that is responsible for these semantic errors? It is clear that the errors are not made consciously and deliberately in response to some kind of articulatory blocking of a fairly peripheral nature. We can illustrate this from G.R.'s attempts to read homophonous noun – function word pairs:

witch → 'witch';	*wood* → 'wood';
which → 'Don't know';	*would* → 'Don't know';
bee → 'bee';	*inn* → 'inn';
be → 'Small words are the worst';	*in* → 'those'.

(On lexical decision tasks G.R.'s performance is close to perfect with visual presentation; function words are no exception to this finding.)

Perhaps, then, there is some more 'central' word-finding difficulty? Some of G.R.'s circumlocutory responses seem to point in this direction:

cottage → 'house...cottage';
courage → 'a drink...courage';
foreign → 'overseas...foreign';
medicine → 'something in a bottle...doctors...medicine';
deer → 'I know it...all over the parks...I can't say the name';
dive → 'can't say the name...down deep...helmet'.

Such responses might be regarded as analogous to the tip-of-the-tongue states that are seen in normal subjects. However, there are other circumlocutory utterances that are a considerable embarrassment for any traditional word-finding interpretation:

female → 'female...**woman**';
brave → 'brave...**deed**';
thirsty → 'thirsty...um, **dry**';
empty → 'bottles...empty, similar to that word';
office → 'yes...the firm...management...office...um...I can't say the name now...I know it! **Manager**';
shower → 'water...you know...shower...I can't say the name'.

(Response words in bold type are the items that G.R. picked as his final choice for the 'correct' response). It is not exactly obvious what the notion of 'word-finding deficit' buys when the patient has said the correct word but failed to recognize that it is correct! Further evidence against any kind of 'response blocking' interpretation can be obtained from sorting and categorization tasks that do not require an overt verbal response. For example, errors are made when G.R. is asked to sort cards with the names of, for example, tools and vehicles into the relevant superordinate categories; even more errors are found when, to acoustic presentation of a word (e.g. 'hammer') the patient is required to point to the appropriate written form in a set of ten tool-names. G.R. also makes errors in a word–picture matching task. Here a single word is presented in each trial and the response is to point to the appropriate picture in an array that contains 'distractor' items of various types. With written word stimuli, numerous errors are made when the distractor picture bears a semantic relation to the correct response (e.g. *lamp* → BULB; *needle* → COTTON REEL; *stethoscope* → SYRINGE). When the stimulus words are presented orally, such semantic errors also occur, although at a much lower rate than with written stimuli. The particular errors made with auditory presentation are a proper subset of those made with visual presentation (Newcombe & Marshall 1980*a*). When performing this matching test with written stimuli, G.R. sometimes reads out the word while pointing to the picture. This occasionally leads to responses of the following kind:

goat → 'sheep' (GOAT);
crocodile → 'tiger' (CROCODILE);
violin → 'flute' (TRUMPET).

(The items in small capitals represent a pointing response to a picture.) On one trial the reverse error occurred:

grave → 'grave' (COFFIN)

Although semantic errors do, then, occur with auditory presentation, there is a very severe imbalance between their rate of occurrence in the auditory and visual modalities. Semantic errors are also more frequent (and less likely to be corrected) when G.R. is reading than when he is naming line-drawings of objects. A further discrepancy lies in the fact that, although G.R.'s spontaneous speech is agrammatic, the severity of the deficit (failure to express 'function words' overtly) is nowhere near as extreme in spontaneous speech as it is when reading either individual words or sentences. And indeed subjects with deep dyslexia have been described who show no trace of agrammatism in spontaneous speech (Low 1931; Shallice & Warrington 1975; Saffran *et al.* 1980). The possibility arises then that deep dyslexia should be interpreted as a modality-specific deficit consistent with Warrington's (1975) postulation of distinct modality-linked semantic stores. An alternative account (Newcombe & Marshall 1980*b*) preserves the notion of a unique modality-free semantic system. In this approach we suggest that the semantic system is either intrinsically unstable in the normal case or can be rendered so by brain damage; we then postulate that the function of various modality-specific peripheral transcoding devices is to stabilize outputs from the semantic component and 'catch' putative mistakes before they emerge in the form of *overt* errors. In reading aloud (in an alphabetically written language), the most obvious stabilizing device is the so-called 'grapheme–phoneme conversion route'. It is precisely this device that we know to be severely damaged or totally inoperative in all cases of deep dyslexia. If the direct (non-analytic) connections between the visual word form system and the phonological lexicon are also destroyed, semantic errors will be allowed to emerge unchecked, and indeed unavailable to correction or awareness by the patient.

4. Separation of formal and semantic similarity

In 1668, John Wilkins, the first secretary of the Royal Society, published his *Essay towards a real character and philosophical language*. In the essay, Wilkins invented an orthography in which the dimensions of visual and semantic similarity were perfectly correlated. Thus 'shrub', for example, was to be written as  and 'tree' as  ; i.e. words of similar meaning were written in forms of similar shape. This orthography may indeed be 'philosophical' in that the physical form of the orthography points directly to the taxonomy of the world that seventeenth-century Fellows of the Royal Society had constructed. From the point of view of a fallible biological mechanism, however, this is exactly what is *not* wanted in an orthography. When reading quickly, words of similar shape (e.g. *tree* and *free*) are easy to confuse with each other. The message *Cut that tree down* does not make sense if *tree* is misread as *free*. But if, as in Wilkins's orthography, the meaning SHRUB was represented as *free*, the misreader would have no independent internal check upon his mistake. I shall end, then, with a fifth principle

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of effective writing systems. In a good orthography, the dimensions of formal and semantic similarity of the code items should be orthogonal to each other, and there should be in the brain separate 'reading routes' that are responsive to the dimensions of visual, phonological and semantic similarity. The striking errors found in surface and deep dyslexia illustrate some of the problems that can arise when only a single route is employed in reading, when, consequent upon brain damage, the *psychological* dimensionality of an orthography is reduced.

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