MATHEMATICAL DISABILITIES

A COGNITIVE NEUROPSYCHOLOGICAL PERSPECTIVE

edited by

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of Phonographic and Logographic Single-Digit Numbers by the Two Hemispheres

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In planning the inclusion of the topic of this chapter in a book devoted to acquired mathematical disabilities. the editors must have assumed not only that the theoretical problem is interesting but also that the literature contains enough relevant data to discuss the issues. A full assessment of the differential roles played by each hemisphere in dealing with different surface forms of numbers would require the availability of results from a variety of tasks comparing different kinds of number representation. Ideally, each task should also have been investigated in the conditions resulting from the combination of different number surface forms with left and right hemifield presentations, or with left and right brain injuries. However, such is certainly not the case, and many conclusions will have to be drawn from experiments in which the requisite conditions are only partially met. The existing data further impose two restrictions on the scope of the review: Only single-digit numbers (hereafter referred to as "numbers," unless otherwise specified) are considered and only nonmathematical tasks are dealt with.

Before speculating on cognitive processes and mental representations of numbers, we should have a good description and classification of what is represented in the stimulus. In spite of the restriction of this chapter to the differential processing of single-digit numbers according to their surface form, some space is also devoted to specifying the notational principles that underlie multidigit number writing. The fact that the resulting classification of symbols that will emerge is different for single-digit and multidigit numbers may highlight what we expect to find, and what has already been found, when these symbols are considered from the vantage point of the cognitive neuropsychology of number processing. The first of the five sections comprising the chapter is therefore devoted to an analysis of different types of number representations. This is followed by three sections reviewing and discussing the data from (a) numerical size comparison tasks, (b) lateral hemifield presentations, and (c) the performances of brain-damaged patients. The fifth section summarizes the main conclusions.

NUMBER REPRESENTATIONS

The arabic numeral *5*, the roman numeral *V*, the English written word *five*, and the corresponding Chinese character are different arbitrary symbols that denote the same abstract concept: the number five. In addition to having different surface forms, these various symbols also belong to different notational systems when they are used as components of multidigit numbers. Two distinctions have to be made. One concerns the difference between numerals and number names and the other, the difference between logographic and phonographic number representations. The first distinction is better captured by characterizing multidigit number notational systems and the second is better illustrated by specifying the surface form of single-digit symbols.

Notational Systems

The first important distinction to bear in mind concerns the difference between numerals and number names. Numerals are special symbols for representing numbers visually. In many written languages they coexist with number names, which are translations of the spoken form, according to the writing system of the language. The only numerals extensively used now are arabic numerals. The universality of arabic numerals contrasts with the language specificity of number names, but the main reason for distinguishing between numerals and number names lies elsewhere: Only number names allow for a term-by-term translation of the spoken multidigit numbers. In other words, we may write and say "two hundred and thirty three," but we do not usually say "two-three-three" or "hundred-hundred-ten-ten-ten-one-one-one" when we are confronted with 233 and CCXXXIII. Hence, the rules governing the way in which numbers are transcribed differ according to notational systems.

These rules are better illustrated by Chinese number writing instead of by English or some other alphabetically written language, and by hieroglyphic Egyptian instead of roman numerals. This allows us to capture the essence of the underlying notational principle without having to deal with irrelevant and confusing features, such as the use of special words to denote the multiple of 10 in English number naming or the incorporation of a subtractive principle in the roman numeral system (e.g., IV instead of IIII). For the few following examples, let us represent the ranks of the units, tens, and hundreds by U, T, and H, respectively.

In the form of hieroglyphic Egyptian used for lapidary inscriptions, one symbol denoted the unit and a different symbol denoted each of the successive powers of 10 up to 10,000. The number 543 was written in the form, HHHHHTTTTUUU. The only important aspect of this representation is that it is based on an additive principle. The conventional grouping of the units of the same rank and the usual order of writing were irrelevant to the understanding of the number. On a stone monument of ancient Egypt, the number would have been written right to left (instead of left to right as here) and the symbols would probably have been displayed on more than one line, but our sequence would have been unequivocally understood, even if it had been written TTHHUHTTHUHU. The same commutative principle applies to roman numerals, except that elements entering into a subtractive relation must be kept together in their conventional order.

The Chinese number-naming system is also based on an underlying additive principle, but a supplementary multiplicative principle allows for suppression of the cumbersome repetitions of the symbols belonging to the same rank. This entails a different symbol for each unit (u1, u2, . . ., u9). The Chinese 543 is therefore written in the form, u5Hu4Tu3, using five different symbols instead of the three needed in hieroglyphic Egyptian. Here too, provided the symbols entering into a multiplicative relation are kept together, permuting the terms would not transform one number into another. In this case, however, the psychological impact of doing so would be stronger, because although the order of the elements plays no intrinsic role in the representation, their usual order corresponds to their order of utterance in the spoken number. Similarly, it may be unusual to write "twenty eight and four hundred" but it clearly means 428. The Chinese number-writing principle has been called a "named place-value" notation by Menninger (1969), as opposed to the "abstract place-value" notation realized with arabic numerals. English number-name writing is also a named place value and it should be clear from what we have said that it is a pseudopositional system.

The only true positional number-writing system still in use was developed some time in the first half of the 6th century A.D. in India, whence it spread more or less rapidly to the whole world. The system uses only 10 symbols, named arabic numerals after their first principal propagators rather than after their creators. In this system the rank of the units is abstractly symbolized by the position occupied by these units in the written number. Permutations of terms are no longer allowed without changing the value of the number and the whole system works only because of the great intellectual accomplishment of symbolizing nothing by something; namely, by using zero to fill in the positions of the unemployed ranks (compare the English three thousand and twenty, in which nothing stands for the unused ranks of the hundreds and the units, with 3,020).

Aside from the Greeks' ephemeral use of a complete abstract place-value system including a zero, the only known independent invention of such a notation took place in Mesoamerica. The extent to which the Mayas really grasped the concept of zero is likely to remain controversial forever, but they undoubtedly used a symbol functionally equivalent to zero in their place-value notation of numbers (e.g., Kelley, 1976).

In Europe, widespread use of the arabic numeral place-value notation began toward the end of the 15th century, rapidly supplanting the roman numerals from then on. The most important consequence of this event is that calculation, mainly realized by means of counting boards and quite independent of number writing before this date, now became intimately bound to the arabic numeral notational system.

Much of what precedes can be found in the extensive and insightful coverage of the topic by Menninger (1969; see Flegg, 1983, for a condensed account). From an information-processing point of view, this rapid survey of the number notational systems still in use reveals three important points.

1. The arabic numerals stand alone in being the only symbols that enter into an abstract place-value notation, an inherently positional system, and in being used for purpose of calculation, a highly specialized cognitive activity of symbol manipulation.

2. Number names, whether written in an alphabetic script, such as English, or in a logographic script (see below) such as Chinese, constitute a different notational system whose purpose is mainly to provide a visual term-by-term translation of spoken numbers.

3. Unlike arabic numerals and number names, roman numerals are more concrete representations of numbers, combining some properties of tally counts with simple additive and subtractive rules. They are quite easily decoded, but they are no longer widely used, and they have never been considered an efficient medium for calculation.

Symbol Surface Forms

Number names are represented according to the writing systems in use for general writing purposes. We therefore distinguish between logographic and phonographic systems. In a logographic system the written symbols represent linguistic units of meaning; namely, morphemes. In phonographic systems the linguistic units represented by each symbol are phonological, being either syllables in syllabic systems of phonemes in alphabetic systems (see Gelb, 1963, for a history and description of the writing systems. For discussions of the psycholinguistic aspects of the written symbols and their consequences for the analysis of mental processes involved in reading, see Gleitman & Rozin, 1977; Henderson, 1984; Holender, 1987; Liberman, Liberman, Mattingly, & Shankweiler, 1980; Mattingly, 1984; Rozin & Gleitman, 1977).

In Chinese writing, the most complete logographic system ever designed and still in use today, each symbol represents one morpheme. Each morpheme is also a word, although many words are composed of more than one morpheme, and are therefore written with more than one character. Chinese characters are often called ideograms, but this terminology is misleading because few characters are actually designed on a truly ideographic principle. We call the characters *logograms* to fit the linguistic description of the unit they represent.

As already mentioned, nine symbols represent the numbers one to nine in Chinese. The first three consist of one, two, and three horizontal strokes and the others are arbitrary symbols. Thus the first three symbols are built on an ideographic, or even a pictographic, principle, representing the beginning of a stick count. Knowing that they stand for numbers, someone who cannot read Chinese at all would be able to interpret them correctly; but this is not the case with the symbols for the numbers four to nine. It is nonetheless clear that the two horizontal strokes stand for the monomorphemic word meaning *two* in Chinese and that the arbitrary symbol representing the number "six" stands for the monomorphemic word meaning *six* in Chinese. Hence, the exact nature of any of these symbols is certainly better captured by the term logogram than by any other term.

In Japan, many Chinese characters, called kanji characters, have been borrowed to be used conjointly with a syllabary. The simple syllabic structure of Japanese allows any word of the language to be written by using only the symbols of the syllabary. These symbols are called kana and they exist in two forms: hiragana and katakana. In a normal text the content morphemes (mainly nouns, verbs, and adjectives) are usually written in kanji and the grammatical morphemes are written in hiragana; foreign loan words are written exclusively in katakana.

Japanese number names are represented in kanji, the characters being exactly those used in China. Like any other words they can also be written in hiragana and katakana, but this seldom, if ever, occurs in daily life. This point should be kept in mind in interpreting the results of experiments that have exploited this possibility.

The most important point of this entire discussion is that although the 10 arabic numerals can be considered as logographic representations of the numbers zero to nine, the nine Chinese (or Japanese) logograms (zero not being represented) are not numerals, but number names. This fact has not always been correctly evaluated, either in the recent psychological literature, or by Menninger (1969) who was struck by the fact that the Chinese number symbols realize a perfect synthesis, being both numerals and number names. That this position is incorrect can be appreciated from the fact that throughout history, Chinese number names have coexisted with genuine autochthonous numerals (incorporating the Indian zero, but not the other symbols, in the 13th century). These have now been replaced by arabic numerals. Hence, the relation between Chinese characters (or Japanese kanji), denoting single-digit numbers, and arabic numerals is exactly the same as that between the corresponding English alphabetically written words and these very same arabic numerals.

This is, of course, the conclusion we reached in our discussion about number notational systems. It is clear that symbols do not lose their identity as number names or as numerals when they denote single-digit numbers. Nevertheless, in dealing with single-digit rather than multidigit numbers, processing operations should be more dependent on the surface form of the symbols than on the notational system to which these symbols belong. Therefore, in investigating the processing of single-digit numbers considered as lexical units, it is a priori more natural to regroup the symbols with respect to their surface forms irrespective of the notational system. Accordingly, in what follows, arabic numerals and Chinese or Japanese kanji number names are subsumed under the logographic category[1], and the generic term *phonographic* is applied to number names written alphabetically or in hiragana (hereafter simply referred to as kana because the katakana form has not yet been used).

Roman numerals are part of a different notational system, but their surface form can be considered as logographic.

NUMERICAL SIZE COMPARISON JUDGMENTS

A common experimental task calls on subjects to judge which of two simultaneously presented arabic numerals is the larger (less often, the smaller) numerically, with response latency as the dependent variable. Such experiments have provided a rich pattern of results revealing at least four different effects: symbolic distance, serial position, semantic congruity, and size congruity. This abundance of effects (not confined to the comparison of number numerical sizes, but apparent also in many other comparative judgment tasks) has recently been the subject of much theorizing (see Banks, 1977; Moyer & Dumais, 1978, for reviews). For our purposes, the main point of interest is the possibility of observing different configurations of results as a function of the surface form of the numbers. In what follows, each effect is briefly characterized and studies contrasting different types of number representations are reviewed and discussed.

Symbolic Distance Effect

The latency of the comparative judgment is an inverse function of the subtractive difference between the two numbers; for example, subjects are faster in judging that 7 is the larger in a pair like 2–7 than in a pair like 5–7 (Aiken & Williams, 1968; Banks, Fujii, & Kayra-Stuart, 1976; Buckley & Gillman, 1974; Duncan & McFarland, 1980; Moyer & Landauer, 1967; Parkman, 1971; Sekuler & Mierkiewicz, 1977). The effect is also observed when numbers are symbolized by patterns of dots (Buckley & Gillman, 1974) or with numbers written in kana and in kanji (Takahashi & Green, 1983). In the latter study, distances of 1, 3, and 5 were compared; the general trend was the same for both kinds of script, but the detailed pattern of results was slightly different in each case. With kana stimuli there was a relatively small decrease in reaction time between distances 1 and 3 and a relatively large decrease between distances 3 and 5, whereas with kanji the opposite configuration was observed, a large decrease between distances 1 and 3 and a small one between distances 3 and 5. Because only 12 out of the 36 possible pairs were studied, the effect could have arisen from an interaction between the relative coding difficulty of the pairs, symbolic distance, and type of script, rather than from a different comparison process taking place with each kind of script. This is a likely possibility in view of the absence of interaction between symbolic distance and type of script (arabic numerals vs. alphabetic number names) in the experiment of Foltz, Poltrock, and Potts (1984, Experiment 2). In this case, the complete set of 36 pairs was used.

Serial Position Effect

In the present framework, serial position refers to the position of each member of a pair of numbers relative to the boundaries of the ordered sequence of single-digit numbers. For a given symbolic distance, pairs composed of small numbers (e.g., 1–3, 2–4) are compared more rapidly than pairs composed of large numbers (e.g., 6–8, 7–9). The effect, often expressed as an increase in reaction time as a function of the increase in the smaller member of each pair, has been consistently observed with arabic numerals (Aiken & Williams, 1968; Buckley & Gillman, 1974; Parkman, 1971). As for symbolic distance, the serial position effect was also obtained with numbers symbolized by patterns of dots (Buckley & Gillman, 1974), and there was no interaction between the serial position effect

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[1] What is at issue is the distinction between semasiographic and glottographic visual messages. A glottographic message is a translation of an actual or a potential spoken utterance, each word (or morpheme) being represented in its correct position. All present-day writing systems are glottographic. A semasiographic message conveys meaning directly without being related to a unique spoken utterance. The positional system of number notation based on arabic numerals is clearly semasiographic, not glottographic. The theoretical position taken in the present chapter is that arabic numerals used in isolation may nevertheless be considered glottographic because they are in a one-to-one correspondance with words of the spoken language. As such the 10 symbols are logographic representations because nothing in their design refers to phonological segments of the words they stand for. This position departs from that of Edgerton (1941) who denied the glottographic nature of single digits on the ground that they may not always be pronounced (e.g., 2 in 2nd) or word order may sometimes be reversed (e.g., $5). Further discussion about these questions may be found in Holender (1987).

and the type of script (arabic numerals vs. alphabetically written names) in the study of Foltz et al. (1984, Experiment 2).

Semantic Congruity Effect

This effect was identified by Banks, Clark, and Lucy (1975). It results from an interaction between the way the instructions are formulated with respect to the boundaries of the ordered set of numbers and the position of the pair of numbers with respect to these boundaries. With small numbers (e.g., 2–4) subjects make their comparisons more rapidly under the instruction "choose the smaller" than under the instruction "choose the larger." Conversely, with larger numbers (e.g., 6–8) decisions are reached more rapidly under the instruction "choose the larger" than under the instruction "choose the smaller." The semantic congruity effect has been observed twice with arabic numerals (Banks et al., 1976; Duncan & McFarland, 1980). Although the effect has not yet been investigated with other number representations, it is unlikely that the outcome of such a study would show differential effects according to the surface form of the numbers. One reason for this is that in judging the size of two objects or the intelligence of two animals, the semantic congruity effect has been found to be independent of the representation of the referents as pictures or as alphabetically written names (Banks & Flora, 1977).

At present, the picture that emerges from contrasting logographic and phonographic representations of numbers in numerical comparison judgments is incomplete, but quite consistent. As regards the symbolic distance and serial position effects there is no evidence that the task is performed differentially according to the surface form of the stimuli, and with respect to the semantic congruity effect the relevant information is not yet available. For the size congruity effect, to be described next, the results are more contradictory; this is also the case for experiments using lateral hemifield presentations in numerical size comparisons. In order to draw some tentative conclusions from these data a more detailed analysis will be necessary than has sufficed for the three effects discussed before.

Size Congruity Effect

This effect, labeled by Banks and Flora (1977), was first observed by Paivio (1975) in a size comparison task involving objects represented either by pictures or by words. It appeared in a Stroop-like situation in which an irrelevant dimension, the relative physical size of each member of a pair of stimuli, was combined orthogonally with the relative real sizes of the referents. In a congruent trial the stimulus referring to the larger object was also physically larger than the other. In an incongruent trial the stimulus referring to the larger object was physically smaller. Neutral trials in which both members of the pairs of stimuli were the same physical size were also included. Paivio observed a size congruity effect with pictures, the mean response latency being 89 ms faster for congruent than for incongruent trials. The most striking result was that there was no congruity effect at all when the same referents were represented by words instead of pictures. As regards number comparisons, this Stroop-like task was first used by Besner and Coltheart (1979) who obtained results parallel to those of Paivio; namely, a large size congruity effect with arabic numerals and no effect at all with the alphabetical representations of the numbers. Subsequent experiments confirmed the result with arabic numerals, but were discrepant with the initial study in showing a large size congruity effect with alphabetical number names as well (Besner, Davelaar, Alcott, & Parry, 1984; Foltz et al., 1984; Peereman & Holender, 1984). The size congruity effect was also observed with numbers written in kanji whereas kana numbers showed ambiguous results (Takahashi & Green, 1983).

Table 3.1 summarizes the main results of the experiments published so far, except for some forthcoming data of the second author (Peereman, in preparation). In addition to presenting the mean reaction time for each type of trial (congruent, neutral, and incongruent), the table also splits the congruity effect into facilitation and interference effects. The facilitation effect is obtained by subtracting the mean latency of congruent trials from the mean latency of neutral trials, whereas subtracting the latter from the mean latency of incongruent trials yields the interference effect. A few more procedural details are worth describing before we discuss the results. In some experiments the numbers were presented side by side, to left and right of a fixation point, and responses were made on a left and right response key (Besner & Coltheart, 1979, logographic condition; Foltz et al., 1984; Henik & Tzelgov, 1982). The other experiments used numbers displayed above and below a fixation point, and responses were made either on two vertically aligned response keys (Besner & Coltheart, 1979, alphabetic condition; Takahashi & Green, 1983) or by activating a forward-backward switch (Peereman & Holender, 1984; Peereman, in preparation,). Only one study used the complete set of 36 pairs generated by using the numbers 1 to 9 (Foltz et al., 1984), whereas the others used only a small subset of these pairs, from 4 to 12 according to the experiment. In addition to central presentations, Peereman and Holender (1984) also included lateral ones and Peereman (in preparation) contrasted the usual manual response with a vocal response, the naming of the larger number.

The left side of Table 3.1 shows the results with logographic scripts, i.e., kanji numbers in the experiment of Takahashi and Green (1983), and arabic numerals in all the other cases. The main results can be summarized as follows.

1. There is a large overall size congruity effect (sum of the facilitation and interference effect in Table 3.1) in each experiment. The magnitude of the effect tends to increase with the increase in the absolute level of performance.

2. Both the facilitation and the interference effects are substantial in each experiment (except for a very small facilitation effect in the experiment of Besner

TABLE 3.1
Size Congruity Effect in Numerical Size Comparison Judgments

Authors	*Experiment or condition*	*Logographic* *C*	*N − C*	*N*	*I − N*	*I*	*Phonographic* *C*	*N − C*	*N*	*I − N*	*I*
Henik & Tzelgov, 1983[a,b]	Exp. 1	588	36	624	72	696	—		—		—
Besner & Coltheart, 1979[a]		531	11	542	44	586	800		—		800
Foltz et al., 1984	Exp. 2	564	21	585	56	641	749	13	762	33	795
Peereman & Holender, 1984	Central field	472	28	500	61	561	719	5	724	32	756
	Left field	481	42	523	54	577	717	38	755	22	777
	Right field	472	56	528	49	577	704	41	745	14	759
Peereman, in preparation	Manual response	520	32	552	70	622	749	35	784	21	805
	Vocal response	568	34	602	92	694	751	17	768	27	795
Takahashi & Green, 1983[a,c]		752	38	790	65	855	1076	−22	1054	41	1096

Note. C = congruent, N = neutral, I = incongruent.
[a] Data estimated from a graph.
[b] First session only.
[c] Data pooled over sessions 1 and 2.

and Coltheart). With central presentations, the magnitude of the facilitation effect is in the range of 20% to 60% of the magnitude of the interference effect. With lateral presentations (Peereman & Holender, 1984), the ratio of the two effects is closer to 1.

3. The kanji numbers used by Takahashi and Green (1983) behave in pretty much the same way as the arabic numerals used in the other experiments, except that response latencies are much longer than with arabic numerals, probably because kanji numbers are not widely used.

The right side of Table 3.1 shows the results for phonographic scripts, the syllabic kana writing in Takahashi and Green's report, and alphabetic writing in all the other cases. The most prominent aspects of the results are the following.

1. Overall response latencies are in the range of 200 to 250 ms longer than with logographic numbers. The absence of a congruity effect, reported by Besner and Coltheart (1979), is not confirmed in subsequent experiments, although the effect tends to be a bit smaller than with logographic numbers. There is no systematic relation between the absolute level of performance and the magnitude of the size congruity effect.

2. With central presentations, much of the size congruity effect is due to the interference caused by incongruent trials, congruent trials provoking almost no facilitation or even a detrimental effect (Takahashi & Green, 1983). With lateral presentations, the opposite tendency is observed; that is, strong facilitation effects and weak interference effects (Peereman & Holender, 1984).

3. Kana numbers (Takahashi & Green, 1983) are responded to much slower than alphabetic numbers, but this form of representation is almost never used outside the laboratory. There is also a reversal in the facilitation effect.

The most important point to discuss is the discrepancy between the absence of a congruity effect with alphabetic numbers in the experiment of Besner and Coltheart (1979) and the presence of such an effect in the two other experiments (Foltz et al., 1984; Peereman & Holender, 1984). Foltz et al. interpreted the difference between their results and those of Besner and Coltheart as due to their use of a repeated-set design instead of the fixed-pair design of the conflicting experiment. In a repeated-set design each item (the number 1 to 9) is paired equally often with each other item, whereas only a small subset of these pairs is used repeatedly in a fixed-pair design (12 pairs repeated 20 times and 9 pairs repeated 10 times in the logographic and alphabetic conditions of Besner and Coltheart, respectively) and each item is paired with only a few other items (one, two, or three in Besner and Coltheart's experiment). It is argued that there is an increasing probability of bypassing the comparison stage as a function of the increase in the number of repetitions in the fixed-pair design: Subjects may respond on the basis of specific response-pair associations established during the experiment. This accounts for the lack of a size congruity effect in Besner and Coltheart's fixed-pair design and the presence of such an effect in Foltz et al.'s repeated-set design. Moreover, the prediction was nicely supported in a study using names of objects (Experiment 1 of Foltz et al.) and the fixed-pair design of Paivio (1975, six pairs repeated eight times, each item being paired with only one other item); no size congruity effect was observed. However, with an infinite-set design in which 48 different pairs were presented only once, as if they were drawn from an infinite set of pairs, a strong 115-ms size congruity effect was obtained, which reduced to 49 ms after three further presentations of the set. Recently, Besner et al. (1984, p. 127) also alluded to the observation of a size congruity effect in using a larger set of alphabetic numbers than in the original experiment of Besner and Coltheart (1979). There is, however, one result that is clearly at odds with this interpretation. In our alphabetical condition (Peereman & Holender, 1984), only four different pairs were repeated 72 times, each of four numbers being paired with only two other numbers. This should have maximized the chances of bypassing the comparison stage, thereby suppressing the size congruity effect, but this did not happen.

A further assumption is needed to account for the fact that the repeated-set design does not suppress the size congruity effect when arabic numerals are used instead of alphabetic number names. Foltz et al. (1984) suggested that because pictures or arabic numerals provide much shorter latencies than their spelled names, retrieving and comparing the size information could be faster than retrieving the appropriate previously learned response in the former than in the latter case. This is a completely ad hoc interpretation. In addition, it cannot explain why, in a fixed-pair design, Takahashi and Green (1983) observed a very strong size congruity effect with kanji numbers in spite of the fact that the absolute level of performance was equivalent to that of Besner and Coltheart (1979) in the alphabetic condition (see Table 3.1). In such a case, according to Foltz et al.'s interpretation, the retrieval of previously associated responses should have been faster than the size retrieval and comparison process, leading to no size congruity effect.

For other tendencies revealed in Table 3.1, such as the smaller congruity effect with phonographic than with logographic script and the different ratios between the facilitation and the interference effect with each kind of script, no unequivocal conclusion can be drawn at present. The problem is that the situation is a little too complicated. Several confounding factors whose roles are not well understood could be responsible for these effects. Moreover, none of them might give any interesting hint toward a possible differential role of the surface form of the stimuli in the operations needed to perform the numerical size comparison judgment. Let us mention two such confounding factors.

1. The relative salience of the irrelevant dimension affects the magnitude of its influence on the decision about the relevant dimension (Besner & Coltheart, 1976; Dixon & Just, 1978). In the present context, the salience of the irrelevant dimension may well be influenced by the factors affecting the judgment of dissimilarity between rectangles, because, roughly speaking, the areas occupied by arabic numerals or by uppercase number names are rectangular in shape. The psychophysics of dissimilarity judgments between rectangles varying in shape and area (Krantz & Tversky, 1975; Wender, 1971; Wiener-Ehrlich, 1978) is surprisingly complex, no simple dimensional structure emerging from the data. There are two ways in which the data discussed in this section could be affected by these psychophysical factors. First, the difference between the physical size of two arabic numerals can simply be more conspicuous than that between two multiletter words, leading to a stronger size congruity effect in the former than in the latter case. Second, the speed with which a dissimilarity judgment can be made, or for our purposes, the speed with which the difference in size becomes compelling, should depend on the magnitude of the physical difference, at least within a certain range. This could be responsible for subtle differences between the magnitude of the interference and facilitation effects according to type of script.

2. From our experience with the task, we know that the magnitude of the congruity effect and the relative magnitudes of the facilitation and interference effects vary considerably between different pairs of numbers, especially with the alphabetical representation. Having used only a small subset of pairs in our experiments, it is hard to find any systematic factor underlying either the intrasurface form or the intersurface form variability. We nevertheless suspect that some pairs are more easily encoded than others, thus affecting the time at which the information becomes available for performing the comparison operation. This could, of course, generate different patterns of results between experiments using different subsets of pairs.

These two confounding factors emphasize the role that the relative time course of processing both the relevant and irrelevant aspects of the pairs of stimuli might play in the determination of the size congruity effect, independent of the comparison process itself. Of course, this could be systematically studied, but we then run the risk of completely losing sight of the real goal of this research, which is precisely to investigate whether or not the surface form of the stimuli affects the numerical size comparison operations, not to untangle the complexity of Stroop-like situations.

Hemifield Presentations

The rationale for using hemifield presentations of stimuli is explained in the next main section of the paper. Suffice it to say here that a relatively better performance for stimuli displayed in one hemifield than in the other is generally interpreted in terms of a contralateral hemispheric superiority for a particular class of stimuli or for a particular experimental task. The investigation of lateral presentations of numbers for comparison of their numerical magnitudes has led to a perplexing picture, because every possible outcome has been reported. Katz (1980, 1981) found a left visual field (LVF) advantage; Besner, Grimsell, and Davis (1979). a right visual field (RVF) advantage; and Peereman and Holender (1984), no difference between fields.

The opposite field advantages of Katz (1980, 1981) and Besner et al. (1979) can be explained by the difference in the exposure durations that were used. A short exposure duration, 50 ms in Katz's experiments, could engender a RVF advantage that has little to do with either the specific material presented or the specific task performed, but is determined rather by the nature of the available visual information (see Sergent, 1983a, 1983b). According to Sergent, the right hemisphere is more efficient than the left in extracting the relevant information from low spatial frequencies than from high spatial frequencies, and vice versa for the left hemisphere. Physical parameters such as very short exposure duration, large stimulus size, and large eccentricity should favor processing on the basis of low spatial frequencies, therefore increasing the odds of finding a LVF advantage whatever the type of stimulus. On the other hand, long exposure durations, such as the 150 ms used by Besner et al. (1979), generally lead to a RVF, which was indeed observed in this particular study. Notice, however, that the authors strongly favored an interpretation of their field advantage in terms of a left hemispheric superiority for performing the comparison process rather than for encoding the stimuli.

Why then, using a relatively long exposure duration of 120 ms, did Peereman and Holender (1984) fail to show any laterality effect? There is no ready interpretation for the discrepancy between their results and those of Besner et al. (1979). However, some tentative suggestions can be made.

The combination of left and right presentations with responses that are also spatialized along the left-right dimension may generate the compatibility effect first reported by Simon (Craft & Simon, 1970; Simon & Rudell, 1967). Asking their subjects to press a right key at the sound of a high tone and a left key at the sound of a low tone (Simon & Rudell, 1967), or to associate the right key with a red bulb and the left key with a green bulb (Craft & Simon, 1970), Simon and his collaborators observed that the right-side response was made faster if the stimulus was presented in the right hemispace rather than in the left hemispace, and conversely for the left-side response. This compatibility effect has been described as a tendency to react toward the source of stimulation. It is genuinely a semantic congruity effect similar to that of Banks et al. (1976), discussed earlier, because the coding of responses in terms of left and right entails an unavoidable influence of the coding of stimulus location in the same terms, thereby facilitating or interfering with the response according to the congruency or incongruency of stimulus and response positions. This compatibility effect has also been observed with lateralized presentations of pairs of numbers. Besner et al. (1979) found that right-index responses were shorter for displays presented in the RVF than in the LVF and vice versa for left-index responses. The same was true for the relation between the rightmost or leftmost finger and the visual field when two fingers of the same hand were used to make the response (Katz, 1981). However, with bimanual responses Katz (1980, Experiment 1) failed to find the effect, a surprising outcome in view of the usual robustness of the phenomenon.

Figure 3.1 illustrates what happens when the side of presentation affects each response in an opposite direction through one factor—compatibility—and in the same direction through another factor—the presumed hemispheric superiority. In Besner et al.'s experiment, the RVF advantage, which is very strong for the right response, gives way to a small (nonsignificant) LVF advantage for the left response. Similarly, in Katz's (1981) experiment, the LVF advantage, which is

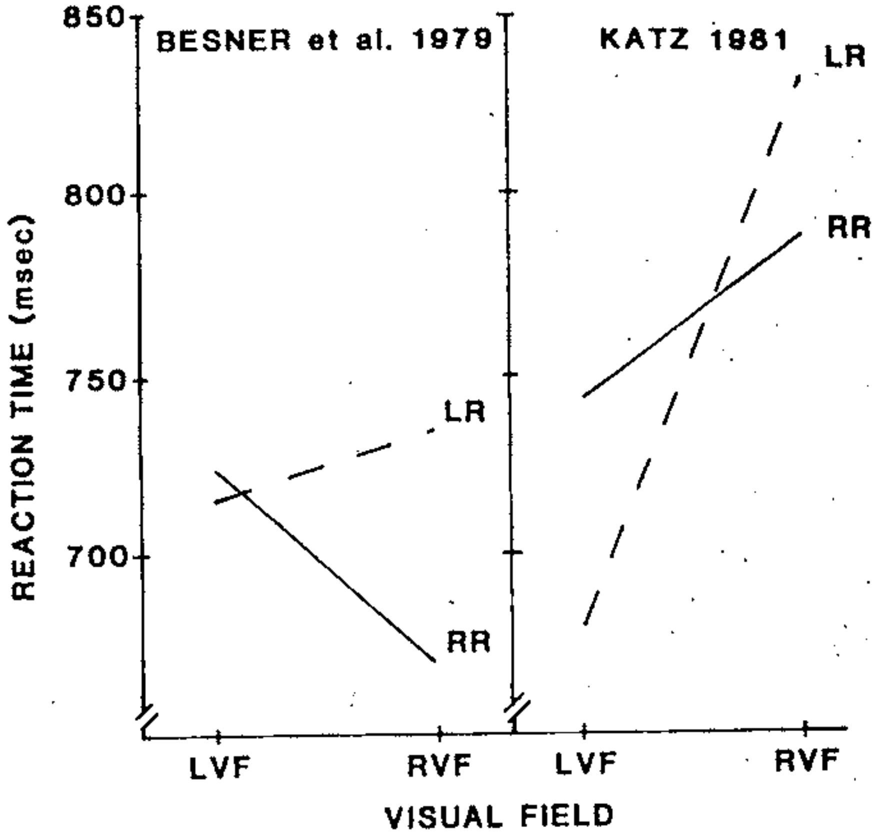

FIGURE 3.1 Mean reaction time for judging which is the larger of two numbers as a function of visual field (LVF = left visual field, RVF = right visual field) and response side (LR = left response, RR = right response) in the experiments of Besner et al. (1979) and Katz (1981). The data were estimated from graphs.

very strong for the left response, is considerably reduced for the right response. The explanation of this phenomenon goes as follows, taking Besner et al.'s results as the basis for the reasoning. For the right response, compatibility and the assumed left hemispheric superiority add their effects to enhance performance with RVF presentations and to impede performance with LVF presentations, thereby inducing a large field difference. For the left response, the advantage of the stimulus being presented in the LVF due to compatibility is counteracted by the disadvantage of being first channeled to the wrong hemisphere, whereas the benefit of the RVF presentation due to left hemispheric superiority is counterbalanced by the cost of being on the wrong side in terms of compatibility, thereby reducing, and even reversing, the field advantage.

The existence of a compatibility effect that interacts in a complex manner with a laterality effect, presumably linked to hemispheric superiority, is an obstacle to the study of this phenomenon per se. It would therefore be better to get rid of the compatibility effect, by suppressing the left-right polarity of the response, presenting the pairs of numbers vertically and replacing the left-right responses with forward-backward responses, exactly the procedure used by Peereman and Holender (1984). If the left hemisphere is really better than the right in performing the comparison process, as Besner et al. (1979) believed, it should be so whatever the spatial disposition of the numbers in the pair, and the ensuing RVF should show up uncontaminated by the compatibility effect. However, as we have already pointed out, the LVF advantage disappeared altogether when we followed this procedure. Thus, the factor that combined with compatibility to determine the pattern of results found by Besner et al. (see Fig. 3.1) was not a left hemisphere superiority for the task, but something else.

What else? We do not know, but we suggest looking to other forms of compatibility that almost certainly play a role when left-right polarized displays and responses are involved in the comparison of the numerical magnitude of numbers. For instance, in deciding which number is the larger, the response is faster if the larger number is on the right side of the pair (e.g., 3–7) than with the opposite configuration (7–3). This effect was as large as 30 ms in the experiment of Aiken and Williams (1968), using 18 pairs among the 36 possible, and 20 ms in Experiment 2 of Banks et al. (1976), using 21 pairs. However, the effect was null in Banks et al.'s Experiment 1 involving only 6 pairs, suggesting possible interactions with specific characteristics of the pairs.

A last point should be stressed. Peereman and Holender's (1984) experiment is the only one fulfilling the requirements of this chapter for numerical size comparisons; that is to say, it is the only study that combines factorially the type of script (arabic numerals and their French alphabetic names) with the side of presentation. It is clear from Table 3.1 that there is no field advantage whatever the type of script, a conclusion that can probably be safely accepted. Whether there is evidence for a differential influence of the type of script on the comparison process cannot be answered on the basis of these data because, as remarked in the preceding subsection concerning the size congruity effect, several possible confounding factors must be controlled before any reliable conclusion can be reached.

LATERAL HEMIFIELD PRESENTATIONS

Rationale Underlying the Approach

From the standpoint of understanding how numbers represented logographically or phonographically are processed, the study of laterality should be considered as one of the tools for analysis of processing operations into components. However, the extent to which the method succeeds in doing so depends on a number of difficult, unsettled issues.

In vision, provided gaze fixation is controlled, it is a matter of anatomical fact that a stimulus displayed laterally in the LVF or in the RVF is first channeled to the contralateral hemisphere and that its access to the homolateral hemisphere depends on its transit through the interhemispheric commissures. The most common interpretation of a better performance in one hemifield than in the other is in terms of a greater ability of the contralateral hemisphere to perform the task. In other words, a given hemifield advantage is almost automatically translated into a contralateral hemispheric superiority. Two points are worth stressing. First, even if a task is fully lateralized (i.e., can be accomplished by only one hemisphere), this need not entail better performance in terms of response latency or accuracy for contralaterally displayed stimuli (see G. Cohen, 1982, for an excellent discussion of this point). Second, besides hemispheric superiority, a number of factors can determine a hemifield advantage. This point has been repeatedly stressed by Bryden (1978, 1982, see also Bertelson, 1982, for a similar case). Our venture at interpreting the contradiction between the results of Besner et al. (1979) and Peereman and Holender (1984) as resulting from a combination of different compatibility effects is a good example of such an alternative approach.

Be that as it may, the logic underlying the study of lateralized presentations of different types of script implies that the results of an experiment should show some kind of interaction between hemifield and type of script. Three different interactive patterns could emerge: (a) opposite visual field advantages for each type of script, (b) no field advantage for one type of script and a field advantage for the other, (c) different degrees of field advantages in the same direction for both scripts. The first pattern is called a nonordinal interaction because each level of one factor (RVF vs. LVF) has an opposite effect on each level of the other factor (type of script). The third pattern is an ordinal interaction because the laterality effect has the same direction for each level of the other factor. The second pattern, in which there is no significant field advantage for one type of script, is a special case of either the first or the third pattern. Among these three possible interactive patterns, the first is certainly the most appealing because it takes the form of a double dissociation between the field advantages and the two kinds of stimuli, and because a nonordinal interaction cannot be removed by a nonlinear transformation of the dependent measure. The existence of such an interaction is therefore relatively independent of the choice of the dependent measure.

Claims for opposite field advantages in processing phonographic and logographic scripts arose from the initial observation of a RVF advantage in the identification of kana words (Hatta, 1978) or nonwords (Endo, Shimizu, & Hori, 1978; Sasanuma, Itoh, Mori, & Kobayashi, 1977), and of a LVF advantage in the identification of kanji words (Hatta, 1977a, 1977b, 1978). Since then, the RVF advantage for processing kana words has been clearly confirmed. Moreover, kanji words composed of more than one character are also better processed in the RVF. For single Chinese or kanji logograms the results are more contradictory because all possible outcomes—RVF, LVF, or no field advantages--have been reported. In spite of this, there is still a widespread tendency to consider that the bulk of the evidence favors the hypothesis of a right hemispheric superiority for the processing of single characters (see Coltheart, 1983, for a recent example). From our reading of that literature, we believe that too many confounding factors could have flawed most of these results for the existing data to be conclusive. If a conclusion is nonetheless to be drawn, we would argue that a right hemisphere superiority for logographic processing is extremely unlikely (see Peereman & Holender, 1985); a view shared by Leong, Wong, Wong, and Hiscock (1985) and by Paradis, Hagiwara, and Hildebrandt (1985).

Review of the Data

The best way to characterize the investigation of lateral differences in the processing of numbers is to say that the data are scarce, the procedures diverse, and the results quite consistent. Most experiments have been concerned exclusively with arabic numerals, although two have included alphabetically written numbers. Let us distinguish between those studies using response latency and those relying on response accuracy as the dependent variable, reviewing the latter first.

Hines, Satz, Schell, and Schmidlin (1969, Experiment 3) inaugurated a series of experiments in which three pairs of numbers were successively presented: One member of each pair was displayed at fixation point, the other either 3° to the left or 3° to the right of fixation. In any particular trial, the lateral member of each pair was always on the same side. (A fourth centrally placed number was temporally interpolated between the third pair and recall in two subsequent studies [Hines & Satz, 1971, 1974].) The task of the subjects was first to recall all the central numbers, and then to recall the lateral ones, only trials with 100% correct central identification being taken into account. The results always showed an overall better recall for right than for left numbers. Further examination showed the RVF advantage to be confined to the first two pairs of a trial, the last pair showing no field advantage. These data are generally disqualified on the ground that the central task in itself can generate a RVF independent of the nature of the stimuli (see Bryden, 1982, for a discussion of this long-standing debate). These data also involve a mixture between perceptual and memory processes without allowing us to disentangle their respective contributions to the RVF advantage, if any.

However, if both members of each pair of stimuli are laterally displayed one in the LVF simultaneously with the other in the RVF (rather than one laterally, the other centrally), a weak LVF advantage may be observed. This effect was not significant in Experiments 1 and 2 of Hines et al. (1969), but reached significance in Experiment 4 of Hirata and Osaka (1967). This LVF advantage could result from the strategy of report, rather than from the nature of the stimuli, the left member of each pair being generally reported before the right one.

Carmon, Nachshon, and Starinsky (1976) reported a higher percentage of recall for two- or four-digit numbers (represented by arabic numerals) in the RVF than in the LVF with fifth- and seventh-grade children. First- and third-grade children were tested only with two-digit numbers, and showed no field advantage. Hatta and Dimond (1980) also reported better RVF recognition of six-digit numbers with adult Japanese and English subjects. However, this RVF advantage might be caused by the combinatorial process involved in forming multidigit numbers rather than by the logographic nature of the representation.

Yet, Besner, Daniels, and Slade (1982, Experiment 1) obtained a very large RVF advantage with single-digit arabic numerals, right presentations leading to 80% correct responses and left presentations to only 40%. In their second experiment, they tested Japanese and Chinese subjects with both kanji numbers and arabic numerals. This time the 14% RVF advantage for arabic numerals was less pronounced than in Experiment 1. Overall performance with kanji numbers was much lower than with arabic numerals, but a 16% RVF advantage was again observed. It is a pity the authors limited their material to the numbers 4 to 9. Remember that in kanji, the first three numbers are concrete representations of the quantity they denote, being composed of one, two, or three horizontal strokes, whereas the other numbers are arbitrary symbolic representations, like arabic numerals. It would have been interesting to compare the laterality effect in the two cases.

We should point out that the extent to which the huge laterality effect obtained in these experiments was caused by physical characteristics of the displays is not known. Given the importance of visual parameters in determining visual field advantages (Sergent 1983a, 1983b), this point is worth stressing. Most studies resort to stimuli physically smaller than the arabic numerals, subtending 5.9° × 8.5°, 4.6° × 5.7°, and 2.0° × 3.3°, in Besner et al.'s Experiment 1 and than the 10.6° × 10.6° stimuli of their Experiment 2. These stimuli were centered 8.8° to the left or right of fixation. The exposure duration was individually adjusted to yield an overall performance of 50% to 60% correct responses, mean durations being 32, 44, and 56 ms for small, medium, and large stimuli in Experiment 1, and 54 ms in Experiment 2. Finally, a 50-ms patterned mask immediately followed stimulus presentation, which is also unusual.

We now turn to studies in which response latency was the dependent variable. Naming latencies for arabic numerals showed no field advantage in the experiment of Gordon and Carmon (1976) and a small, but significant, 10-ms RVF advantage in Experiment 3 of Geffen, Bradshaw, and Wallace (1971). Procedural differences between experiments inspire no special comments. The main parameters of the task were, for Gordon and Carmon (1976) and Geffen et al. (1971), respectively, 7 and 4 different stimuli, exposure durations of 100 and 160 ms, stimulus visual angles of 2° and 0.5°, and eccentricities of 3° and 4°.

With two-choice manual response tasks involving only two arabic numerals, a significant 13-ms RVF advantage was found by Geffen et al. (1971, Experiment 5) and a similar but not significant 14-ms advantage was reported by G. Cohen (1975) in her cued condition. Cohen mixed three different representations of the numbers 4 and 5: arabic numerals, their English names presented vertically, and the corresponding patterns of dots found on a die. Subjects were either cued or not cued about the specific representation to be used on each trial. Under precuing, number names yielded a slightly greater RVF advantage (20 ms) than arabic numerals, and dots showed a nonsignificant 12-ms LVF advantage. Without cuing, there was no field difference, whatever the type of stimuli.

Classification tasks also yield a small RVF advantage with arabic numerals. Geffen, Bradshaw, and Nettleton (1973) used a many-to-one stimulus response mapping in a go-no go task involving four numbers and one vocal response. Two arabic numerals called for the response "bong" and two others required no response. This yielded a 16-ms RVF advantage. In a number-nonnumber classification modeled on the classical lexical decision task, Peereman and Holender (1985) showed a significant 13-ms RVF advantage and a significant 26-ms advantage in the same direction for alphabetically written number names, the interaction between visual field and type of script being nonsignificant.

Tasks involving more complex decisions than those just described have been almost exclusively concerned with numerical size comparison judgments (Besner et al., 1979; Katz, 1980, 1981; Peereman & Holender, 1984); they were reviewed and discussed in the preceding main section. There is only one more study to mention. Hatta (1983, Experiment 1) orthogonally varied the numerical size and the physical size of each member of laterally displayed pairs of arabic numerals, asking his Japanese subjects to perform a congruity judgment. An overall 29-ms RVF advantage ensued. A 47-ms RVF advantage also showed up when the same task was performed with the kanji logograms denoting million units (Experiment 3). By contrast, in judging the congruity between the relative physical size of pairs of logograms and the relative physical sizes of the referents (Experiment 2), the subjects showed a 26-ms LVF advantage. The author interpreted his results as evidence that the comparative judgment is based on different types of mental representation in dealing with kanji object names and with numbers, but that in this latter case, the surface form of the stimuli (arabic numerals vs. kanji words) is immaterial.

Interpreting the Results

There is nothing to indicate that opposite visual field advantages for each kind of script, the first possible pattern of results mentioned above, will ever be found in contrasting numbers written logographically and phonographically. On the contrary, both surface forms lead to RVF advantages. If the LVF sometimes reported with single Chinese logograms is valid, then arabic numerals belong to a small class of logograms behaving differently as regards laterality, as is also suggested by the results of Hatta (1983).

To date, there has been no report of a significant ordinal interaction between visual field and type of script, but the prospect of finding one is quite good. With arabic numerals and simple tasks like naming or categorizing, a RVF of 10 to 15 ms is typically found; this is the lower bound for the effect to be statistically significant. On the other hand, Peereman and Holender (1985) pointed out that the magnitude of their RVF advantage (26 ms) for numbers written alphabetically was more substantial and well within the range of the large RVF advantages typically reported in lexical decisions involving larger classes of words. Hence, there would be nothing very unexpected if a statistically more powerful study in the future came up with a significant ordinal interaction indicating a larger RVF advantage for alphabetic number names than for arabic numerals, both RVF advantages being significant.

Let us assume that the ordinal interaction has indeed been found. What, and how much information would then have been gained regarding logographic and alphabetic number processing? To answer this question, we will be obliged to integrate laterality research into the broader framework of mainstream information-processing analysis—a highly desirable, but so far unfulfilled accomplishment (Allen, 1983; Bertelson 1982). Bertelson optimistically closed his recent analysis of laterality research with the words "Progress can be expected, provided laterality research is conducted as an integral part of the study of human cognition" (1982, p. 203). Taking a few steps in this direction, in search of an answer to the question asked at the outset of this paragraph, we came up with a more distressing conclusion (Peereman & Holender, 1985). An analysis similar to that leading to this conclusion is now presented.

The aim of the analysis is to show how the ordinal and nonordinal interactions described in the rationale for the approach can be interpreted in the relatively constrained framework of a stage analysis of reaction time. The two basic assumptions are as follows:

1. Response latency can be decomposed into a series of additive component durations corresponding to different stages of processing. For additivity to hold, the processing stages should be strictly serial, each stage starting only when the

preceding stage has provided an output. Under these constraints, any modification of the duration of one particular stage under the influence of any factor (i.e., hemifield of presentation) should be reflected in the response latencies. This is one of the assumptions underlying Sternberg's (1969, 1984) additive factor method, one of the most popular methods of analyzing processing into components.

2. Hemispheric specialization is relative rather than absolute: Each hemisphere can perform the task, but one is more efficient than the other. This is more reasonable than the alternative assumption of absolute hemispheric specialization (only one hemisphere can perform the task), which would imply that the difference in latency between visual fields is due to the time needed to transfer information from one hemisphere to the other when the stimulus is displayed on the wrong side. This alternative is unlikely because it would entail a relative constancy across experiments in the magnitudes of the difference between response latencies in the two fields, which is hardly the case (G. Cohen, 1982).

Within this framework, the simplest possible account for the presence of an interaction, either ordinal or nonordinal, between visual field and type of script requires the addition of two specific assumptions. (1) All processing stages are neutral with respect to laterality save one, or at maximum two—let us call them Stages A and B—which can be either neutral or lateralized according to circumstances. In the neutral state of a stage the operations performed during that period take the same mean amount of time in each hemisphere. If a stage is lateralized, the corresponding operations are performed faster in one hemisphere than in the other one. (2) We cannot exclude a priori the possibility that (a) both Stage A and Stage B are lateralized on the same side for both types of stimulus, (b) that each stage is neutral for one type of stimulus and lateralized for the other, or (c) that the two stages are lateralized in opposite directions for each type of stimulus. Within these constraints, each pattern of interaction can be realized in three extreme ways according to the following principles. In each of the three cases, the ordinal interaction is labeled 1 and the nonordinal, 2.

A. Only Stage A is lateralized, Stage B is neutral.

1. Stage A is left-lateralized for both kinds of number representations, but the magnitude of the RVF advantage depends on the surface form of the stimuli, being larger for alphabetical number names than for arabic numerals.
2. Stage A is left-lateralized for alphabetical number names and right-lateralized for arabic numerals.

B. Stage A is left-lateralized for both scripts and produces the same degree of RVF for both scripts.

1. Stage B is neutral for arabic numerals and left-lateralized for alphabetical number names; hence, Stage B adds its RVF advantage to that of Stage A, producing the required interaction.
2. Stage B is neutral for alphabetical number names and right-lateralized for arabic numerals. Stage B produces a LVF advantage sufficient to supersede the RVF caused by Stage A.

C. Stage A is neutral for alphabetical number names and Stage B is neutral for arabic numerals.

1. Both stages are left-lateralized when dealing with their specific stimulus type. It just happens that the RVF advantage due to Stage B is larger than that produced by Stage A.
2. Stage A is right-lateralized for arabic numerals and Stage B is left-lateralized for alphabetical number names.

Within the constraints defined, one can easily find the different possible interpretations corresponding to the third interactive pattern, in which only one type of script shows a visual field advantage. Similarly, the different possibilities corresponding to an absence of interaction can also be worked out.

In performing a similar analysis (Peereman & Holender, 1985), we showed that a significant ordinal interaction is no more informative than a nonsignificant interaction. We now extend this conclusion by showing that the favorite nonordinal interaction is no more informative than the ordinal. Using the simplest possible model for the organization of processing operations, and looking at the interaction between visual field and stimulus type, we always come up with three different possible interpretations. In other words, laterality as a tool for analyzing processing into components simply fails to do its job. One can, of course, retort that nobody ever pretended to disentangle these various alternatives by using the laterality approach. The point would be well taken, but then what is the purpose of presenting all these beautiful phonograms and logograms in the left or in the right visual field? To avoid such criticisms researchers using the laterality methodology should be more explicit about their goals than they usually are.

NUMBER PROCESSING AFTER BRAIN INJURY

The discussion of the data provided by brain-damaged people is divided into two parts. In the first, all patients have lesions affecting different language areas of the left hemisphere. The patients display a variety of aphasic troubles, including alexia with agraphia. Potentially, the investigation of these patients can teach us something about the way different notational processing systems can break down, but the respective roles played by each hemisphere in determining the preserved aspects of performance cannot be ascertained. In the second part of the discussion, data concern the partial or total disconnection of the right hemisphere from the left. These data can potentially tell us something about the competence of the right hemisphere in dealing with different representations of single-digit numbers.

Number Processing with Lesions Located in the Language Areas

What is clear from the fragmentary information available is that the ability to read single- and multidigit numbers represented by arabic numerals can be somewhat preserved in patients unable to read letters and words in the alphabetic code. From the anatomo-clinical study of 183 retrorolandic brain-injured patients, Hécaen, Angelergues, and Houillier (1961) concluded that the frequency with which letter or digit reading breaks down is different according to the site of lesion; this could indicate that partially different functional subsystems are indeed involved in each case. The same authors also mentioned 16 patients who, as a group, showed a relatively stronger inability to identify mathematical signs than arabic numerals. A fully selective loss of this competence has been reported in two patients by Ferro and Botelho (1980). Unfortunately, they did not investigate the patients' ability to identify the written names of the mathematical signs.

We have found one patient-group study in which the ability to process different number surface forms was investigated (Dahmen, Hartje, Büssing, & Sturm, 1982). These authors selected three groups of 20 patients, each group corresponding to a different pathology—Wernicke's aphasia, Broca's aphasia, and right-sided retrorolandic lesion. These groups varied in their identification performance for numbers (chosen in the set 1 to 25), but showed no difference according to the type of representation (arabic numerals or their German names). The mean numbers of correct identifications (out of 20) for arabic numerals and number names were 13.3 and 12.0, 16.2 and 14.8, and 19.7 and 18.0, for Wernicke's aphasics, Broca's aphasics, and patients with a right-side lesion, respectively. The same was true in a numerical size comparison task in which the patients had to point to the larger number in pairs of numbers. For arabic numerals and number names the mean numbers of correct responses were 8.7 and 8.6, 14.2 and 14.3, and 16.2 and 15.9, for Wernicke's aphasics, Broca's aphasics, and patients with a right-side lesion, respectively. Three points should be stressed. First, the difference in performance between Broca's and Wernicke's aphasics is in the direction expected on the basis of the overall differences exhibited by these patients in terms of language comprehension. Second, the results of the comparison task confirm the trend we observed with normal subjects in being unaffected by the surface form of the numbers. Third, unlike the identification process, the comparison process seems to require the integrity of the right hemisphere as indicated by the difference in performance in each task in the group of patients suffering from a right-side lesion.

Most of the data reviewed so far are based on the comparison of the mean performances of groups of patients. Caramazza (1984) has recently pointed out that such an approach is ill-suited for addressing the issue of the analysis of cognitive processes because the patients included in a given group could differ greatly in terms of the mechanisms underlying their performance. The remaining data come either from single cases or from very small, relatively homogeneous groups of patients, whose individual symptomatology is generally available.

The few single-case studies to mention in closing this subsection all concern Japanese patients who offer the additional interest of being able to show a dissociation between the processing of two forms of logographic script (kanji words and arabic numerals). One such aphasic patient was described by Sasanuma and Monoi (1975). He was severely impaired in language comprehension, whether spoken or written. His most prominent symptom was his greater ability to read aloud kana than kanji words, though with little comprehension in either case. This dissociation is extremely rare in Japanese aphasics, most of whom show a differential ability to process each kind of script being better with kanji than with kana words (Sasanuma, 1974a, 1975). Aside from that, the patient was able to carry out arithmetical operations, and he could read and understand arabic numerals.

The other Japanese patients are alexics with agraphia. Strictly speaking, the syndrome consists of a selective impairment in reading and writing, unaccompanied by any trouble in spoken language comprehension and expression. However, this ideal definition almost always overstates the true state of spoken language performance. It would be closer to reality to say that the most prominent syndrome coexists with mild aphasic troubles (e.g., Hécaen & Kremin, 1976). In these cases, reading impairment is always stronger in kana than in kanji. Yamadori (1975) reported one such patient who was severely impaired in calculation and in number reading. Yamadori also summarized two other reports published in Japanese (Kotani, 1935; Ohashi, 1965, cited by Yamadori, 1975) concerning two other cases of alexia with agraphia accompanied by strong calculation impairments.

Sasanuma (1974b) described a case of alexia with transient agraphia. The patient's reading in both kana and kanji was strongly deficient, performance in kanji being a little better than in kana. "Reading of digits, both Arabic and Chinese was impaired also" (Sasanuma, 1974b, p. 93), but less than for kana and kanji. The patient was good at mental calculation, but written calculation was hampered by his reading problem. Six months later almost all symptoms other than alexia had disappeared, but nothing more specific was stated.

Because of his preservation of mental calculation, the patient of Sasanuma (1974b) is sometimes considered as a counterexample to the observations of Yamadori (1975). Such cannot be the case because it is extremely unlikely that the two patients suffered from the same pathology. Yamadori's patient was alexic with agraphia, whereas the patient of Sasanuma presented all the symptoms of an alexia without agraphia (see next subsection) in which preservation of mental calculation is typical (e.g., Geschwind, 1965; Symonds, 1953).

To sum up, most patients with lesions affecting the language areas of the left hemisphere show various degrees of disintegration of their mathematical abilities and a poor ability to read arabic numerals.

Number Processing by the Disconnected Right Hemisphere

For theoretical reasons that become apparent as we proceed, it is convenient to examine successively the data from patients having one of the following characteristics: (a) alexia without agrahia, (b) section of the splenium (posterior part) of the corpus callosum, (c) commissurotomy, and (d) hemispherectomy.

Alexia without Agraphia. An ideal patient with alexia without agraphia cannot read, but can write spontaneously and to dictation, without being able to reread what he or she has written. Such a patient has no trouble in spoken language expression or comprehension, but has some difficulties in visual object naming and a strong impairment in color naming; mental calculation is preserved. The classical account of the syndrome by the pioneer neurologists, as revived and specified by Geschwind (1965), describes isolation of the intact left angular gyrus from each occipital visual cortex. This condition is caused by (a) destruction of the left visual cortex or of the connections between the left visual cortex and the left angular gyrus and (b) destruction of the splenium of the corpus callosum, which cuts off from the left hemisphere the visual information reaching the right intact hemisphere. The essence of the trouble is, therefore, the disconnection of intact language zones from the visual world (but not from the auditory or somatosensory world). Logically, the lesions should entail an incapacity to name any visual scene; this is not the case, although it is partially realized by some difficulty in object naming and a very poor ability to name colors. The supplementary hypothesis needed to account for the preserved ability to name objects is that objects can be recognized (but not named) in the right hemisphere and that it is this interpreted information, not the visual information, that is transmitted to the left hemispheric language areas through the intact anterior portion of the corpus callosum. We assume that the right hemisphere is unable to provide verbal responses (see below). By extension, any reading performance preserved (e.g., for arabic numerals) should reflect right hemisphere competence in processing the information. The same rationale is used by Coltheart (1980, 1983) in his attempt to account for deep dyslexic's preserved reading competence (the etiology of this syndrome is different from that of alexia without agraphia).

The recent literature has usually described four of the six alexic patients of

Hécaen and Kremin (1976) as displaying the symptomatology required to fit the ideal model. They all performed better in dealing with arabic numerals than with single letters or single words. Close examination of the constellation of symptoms displayed by these patients reveals that their classification is problematic: Part of their deficit could well be due to some lesion in the language area of the left hemisphere as well. Lack of space precludes any full analysis of this very complex question here. Only a brief account sufficient to make the point is presented, but it should be kept in mind that including of a patient in one of the subgroups of Table 3.2 is often tentative because we generally lack the decisive anatomo-clinical data to remove the uncertainty. For example, the inclusion of Stengel, Vienna, and Edin's (1948) two patients in the group consisting of close to ideal cases would be disputed by Oxbury, Oxbury, and Humphrey (1969).

Table 3.2 includes many of the cases of alexia without agraphia reported in the literature published in English between 1948 and 1976. All the tabulated cases are bad at reading words, and most of them are relatively better at reading arabic numerals than letters. They can be further differentiated on the basis of several features, among which four have been selected for the present discussion. These features are (a) presence or absence of a right hemianopsia, (b) color-naming performance, (c) spelling performance, and (d) mental calculation performance. Spelling is evaluated either by the ability of a patient to spell and to recognize orally spelled words or by his use of a spelling strategy in attempting to read words. A good mental calculation performance indicates that very simple arithmetic operations can be performed. Here follows the description of the groups.

Group 1: These patients are close to the ideal model in showing an anatomically verified (Cumming, Hurwitz, & Perl, 1970; Geschwind & Fusillo, 1966) or presumed brain infarction (Benson, Brown, & Tomlinson, 1971, Cases 1 to 3; Holmes, 1950; Kreindler & Ionăşescu, 1961; Oxbury et al., 1969, Case 1; Sasanuma 1974b; Stengel et al., 1948). The infarction is of the left occipital lobe (responsible for the hemianopsia) and of the splenium, both caused by some pathology of the left posterior cerebral artery. The 11 patients show a very consistent pattern of results. They all exhibit the right hemianopsia expected from their lesion in the left visual cortex. When investigated, spelling and mental calculation are always good and color naming is always bad except in one case (Cumming et al., 1970). Even the last case does not cast doubt on the homogeneity of this group of patients because the dorsal part of the splenium was preserved in this patient; this could allow for a transfer of the visual color information from the right occipital lobe to the left angular gyrus (see Greenblatt, 1973, for further discussion of this point). It is clear that the case of Sasanuma (1974b) reviewed in the preceding subsection fits perfectly well in this group of patients. It could be tentatively concluded that the right hemisphere of these patients has a much better abilit to identify arabic numerals than letters or phonographically written words.

Group 2: The four cases included in this group are remarkable for their lack of

TABLE 3.2
Tentative Classification of Cases of Alexia Without Agraphia
Reported Between 1948 and 1976

Authors	*Patients*	*Hemianopsia*	*Spelling*	*Mental calcul.*	*Color naming*	*Word naming*	*Letter naming*	*Single digit naming*
Group 1: Close to ideal cases with minimal additional deficits								
Stengel et al., 1948	1	yes	good	good	bad	bad	medium	good
	2	yes	good	good	?	bad	good	good
Holmes, 1950		yes	good	good	bad	bad	bad	good
Kreindler & Ionăşescu, 1961		yes	?	good	bad	bad	medium	good
Geschwind & Fusillo, 1966		yes	good	good	bad	bad	bad	good
Oxbury et al., 1969	1	yes	?	?	bad	bad	medium	good
Cumming et al., 1970		yes	good	good	good	bad	bad	good
Benson et al., 1971	1	yes	good	good	bad	bad	medium	good
	2	yes	good	?	bad	bad	medium	?
	3	yes	good	good	bad	bad	good	?
Sasanuma, 1974b		yes	good[a]	good	medium	bad	—	medium
Group 2: Close to ideal cases with potential additional deficits								
Ajax, 1967	1	transient	good	good	good	medium	good	good
Goldstein et al., 1971		no	?	good	good	bad	bad	medium
Heilman et al., 1971	1	no	good	medium	bad	bad	bad	?
Greenblatt, 1973		no	?	good	good	bad	good	good
Group 3: Nonideal cases with attested additional lesions								
Warrington & Zangwill, 1957		yes	good	bad	bad	bad	medium	good
Ajax, 1964	1	yes	good	good	good	medium	good	good
Kinsbourne & Warrington, 1964		no	bad	?	bad	bad	good	good
Caplan & Hedley-Whyte, 1974		yes	good	bad	bad	bad	bad	bad
D. N. Cohen et al., 1976		yes	?	bad	medium	bad	good	?
Group 4: Hécaen and Kremin's (1976) presumably nonideal cases								
		b	*b*	*b*	*b*	*c*	*c*	*c*
Hécaen & Kremin, 1976	CRO	yes	good	bad	good	20%	100%	100%
	DEL	yes	good	bad	medium	6%	86%	100%
	SAL	yes	good	medium	good	12%	70%	82%
	CLI[d]	yes	medium	bad	medium	0%	0%	32%
	BLA[e]	Quadr. sup.	?	medium	good	30%	20%	92%
	MAG[e]	Quadr. sup.	good	good	good	85%	100%	100%

Note. An ideal case is characterized by (a) a destruction of the left visual cortex or of the connections between the left visual cortex and the left angular gyrus and (b) a destruction of the splenium of the corpus callosum.

[a] Spelling of kana characters.

[b] From Table 1 (p. 298).

[c] Percent correct from Figs. 4 to 9 (pp. 305–308).

[d] Mild agraphia.

[e] Strong agraphia.

right hemianopsia, indicating an intact left visual cortex. This can be related to the etiology of their trouble, which is different from that of patients in Group 1. The cause of the alexia was either a surgical removal of a vascular anomaly (Ajax, 1967, Case 1), a carbon monoxide intoxication (Goldstein, Joynt, & Goldblatt, 1971), a head trauma (Heilman, Safran, & Geschwind, 1971, Case 1), or a tumor (Greenblatt, 1973). In the last case anatomical analysis of the brain showed that the tumor had destroyed the splenium of the corpus callosum and part, but not all, of the connections between the intact left visual cortex and the left angular gyrus. One can tentatively hypothesize that the connections needed to transmit color information to the left angular gyrus were also preserved in two of the other patients. If this were indeed the case, these four patients, showing good spelling and good mental calculation, could be considered examples of the ideal model of alexia without agraphia as good as those of Group 1. However, it seems unlikely, in view of the etiologies of these alexias, that the brain damage was really so selectively localized. We cannot preclude the possibility that the language areas have been more or less affected as well, rendering those cases potentially less conclusive than those of Group 1 with respect to the assessment of right hemisphere competence in number identification.

Group 3: The patients in this group are certainly the least appropriate for our purposes because their left occipital lesion extended to the parietal lobe as well and because we generally do not know whether the splenium was lesioned or not (Ajax, 1964, Case 1; D. N. Cohen, Salanga, Hully, Steinberg, & Hardy, 1976; Kinsbourne & Warrington, 1964; Warrington & Zangwill, 1957). The patient of Caplan and Hedley-Whyte (1974) had an anatomically verified lesion of the left occipital cortex and of the splenium, but she suffered from additional small left parietal lesions. This can explain why this patient had dyscalculia, finger agnosia, and left-right confusion. The heterogeneity of performance in this group contrasts with the homogeneity of performance of Group 1 patients, which could support the idea either of a pathology different from that of alexia without agraphia, or, at least, of the existence of supplementary problems compared with the ideal model. Therefore, these data cannot safely be used to infer anything about right hemisphere competence.

Group 4: This group includes the six alexics studied by Hécaen and Kremin (1976). It is immediately apparent that all six patients would fall in our third group, even though three of them are generally considered as ideal cases of alexia without agraphia (CRO, DEL, SAL). CLI, who is slightly agraphic, is generally assimilated to the nonagraphic patients, whereas BLA and MAG are dissociated from them on the basis of their strong agraphia. It is clear that none of these patients presents the profile of those of Group 1 in having good spelling and mental calculation and poor color naming. Within the group of four patients with a right hemianopsia, only SAL is attested as suffering from a lesion of vascular origin sufficiently selective to affect only the occipital lobe. Although his performances depart from those of patients in Group 1, he is the only one whose inclusion in this group might be defended.

In summary, we can probably safely rely on the patients of Group 1 in attempting to assess the right hemisphere ability to process visual symbols semantically. Some other cases are probably valid as well, but we have enough patients in Group 1 to adopt a conservative position, excluding all others from further discussion.

Section of the Splenium of the Corpus Callosum. The logic of the interpretation of alexia without agraphia implies that, under LVF tachistoscopic presentations, a patient whose only lesion is a section of the splenium of the corpus callosum should exhibit exactly the same reading performance as an alexic without agraphia. To our knowledge, only six such cases have been reported, three of them being examined at a time at which the hemifield presentation technique was not well developed. All six cases had their splenium severed in the process of removing a subcortical small tumor. The patient of Trescher and Ford (1937) could not recognize letters presented in the LVF (for what duration?), but other symptoms, such as a left-hand astereognosis, did not guarantee that the splenium section was the only damage suffered by the patient. The two patients studied by Maspes (1948) did not present any hand astereognosis (for wooden letters). Letters and arabic numerals presented for 1 or 0.5s were very well recognized in the RVF, but not in the LVF, as expected. Three similar Japanese cases have been reported in the recent literature (Sugishita, Iwata, Toyokura, Yoshioka, & Yamada 1978). With RVF brief presentations (66 ms), oral reading and comprehension of both kana and kanji words were almost perfect. With LVF presentations, performance was poorer, being at chance level for kana, but somewhat better than chance for kanji. Moreover, performance improved relatively more with kanji than with kana when the same material was retested two or three times at intervals of several months. Unfortunately, numbers were not tested.

Sugishita et al. (1978) interpreted their results as showing that the right hemisphere can understand the logographic kanji better than the phonographic kana; this is consonant with the better recognition of arabic numerals than of letters or alphabetically written words by alexics without agraphia. It is unfortunate that Maspes (1948) did not systematically investigate the difference in performance for letters and arabic numerals. Sugishita et al. also assumed that the vocal response was given by the left hemisphere, not by the right one. This implies that, however accurately identified the LVF stimuli were, naming could not have been achieved at all if the corpus callosum were completely sectioned. This brings us to the next stage in our review.

Commissurotomy. The initial investigation of patients having undergone a complete section of the interhemispheric commissures revealed the very poor language competence of the right hemisphere in most cases (see Gazzaniga, 1970). However, two patients of the California series (L.B. and N.G.) and three patients of the East Coast series (P.S., J.W., and V.P.) show a considerable right hemisphere language comprehension (both spoken and written). In addition, within 2 years following commissurotomy, P.S. and V.P. have developed the ability to access speech from the right hemisphere (see Gazzaniga, 1983). All these patients have a complete section of the corpus callosum and the hippocampal commissure. Most patients of the California series, including L.B. and N.G., also have a section of the anterior commissure, whereas most patients of the East Coast series, including P.S., J.W., and V.P., do not.

Recognition performance for letters and arabic numerals was investigated in six patients of the California series by Teng and Sperry (1973). In one condition, pairs of letters or of arabic numerals were presented either in the LVF or in the RVF, calling for a verbal report. With RVF presentations 86% of the letters and 80% of the digits were named correctly, whereas with LVF presentations these scores dropped to 13% and 35%, respectively. Notice that one patient, N.W., made 100% errors with LVF presentations of both letters and numerals and that L.B. reported only 22% of letters, but 80% of arabic numerals from the LVF. In another experiment involving fewer numerals (Gazzaniga & Hillyard, 1971), L.B. described a strategy of enumerating the numbers and stopping when the response popped out, which the authors found compatible with the idea that the response was actually generated in the left hemisphere through cross-cuing with the right hemisphere. This strategy should be easier to use with single-digit numbers than with letters because the set is smaller in the former than in the latter case. Whether L.B. or the other often-tested patients used in Teng and Sperry's (1973) experiment were using a similar strategy is not known, but it cannot be ruled out. Hence, these data are not strong enough either to challenge the hypothesis of the muteness of the right hemisphere, or to provide unequivocal evidence of a greater intrinsic ability of this hemisphere to deal with arabic numerals than with letters.

Gazzaniga and Smylie (1984) tested two of the right hemisphere language-proficient patients of the East Coast series, V.P. and J.W. Both patients showed errorless performance in multiple-choice pointing to numbers presented to the right hemisphere (LVF). V.P. was also able to read these numbers aloud perfectly well, whereas J.W. was completely unable to do so. Both patients showed extremely poor performance in carrying out simple arithmetic operations with the right hemisphere.

The data of Gazzaniga and Smylie (1984) are compatible with the idea that the left hemisphere normally subserves calculation (see preceding subsection) and that the right hemisphere can identify numbers. However, multidigit number identification in probably better in these two patients than in most patients showing the ideal symptomatology of alexia without agraphia. The extent to which these data can be generalized to the entire population of commissurotomized patients, and, a fortiori, to normal people, is debatable (see Gazzaniga, 1983, and Zaidel, 1983, for somewhat opposite views on this question).

Hemispherectomy. The last logical step in this story is to assess the number-processing ability of a completely isolated right hemisphere, the left hemisphere having been removed completely (actually the left cortex, the left subcortical structures being almost entirely preserved).

Gott (1973) described such a patient who underwent a left hemispherectomy at the age of 10 years because of malignancy. She had already undergone brain surgery at the age of 8 for removal of a tumor in the left ventricule. When she was tested 2 years after the hemispherectomy, she showed good comprehension of spoken language but very poor verbal expression (mainly single words or short stereotyped sentences) and very poor reading of single words. She was unable to name a single letter presented visually or to choose above chance (30% correct) which of four visually displayed letters was the one just spoken by the experimenter, but she performed much better in this task when arabic numerals were used instead of letters (80% correct). When Zaidel (1976) tested her one year later, using a similar procedure, she was a little better in pointing to a spoken multidigit number (out of six) than to a spoken letter.

The description given by Hillier (1954) of the performance of his patient is more anecdotal. After three surgical interventions in the left hemisphere during the preceding 15 months, a complete hemispherectomy was finally performed. The patient was 14 years old at the time of the first intervention. Each intervention left him with severe aphasic troubles, indicating that language functions were subserved by his left hemisphere. However, after hemispherectomy, he was described as having good comprehension of spoken language and an ability to say some words and to read single letters.

However poor the verbal performance of these two patients may appear, it is nevertheless much better than would have been expected if the right hemisphere were completely unable to subserve any linguistic function. Due to the youth of the patients, no generalization of this conclusion is allowed because the plasticity of the nervous system is probably still important at that age. This plasticity is now well documented in patients who have undergone hemidecortication because of infantile hemiplegia, accompanied by intractable seizures. It is clear that if the illness starts before the age of one year the healthy hemisphere, whether right or left, subserves all the functions normally shared between two hemispheres (McFie, 1961). In these cases it requires subtle testing with tasks varying in complexity to show that patients retaining their left hemispheres are relatively better at complex syntax comprehension than those retaining their right hemispheres (Dennis, 1980a; Dennis & Kohn, 1975), whereas the opposite relation between relative levels of performance holds for complex spatial tasks (Kohn & Dennis, 1974). Hence, behind the tremendous plasticity shown by each hemisphere in developing functions for which it is usually less proficient, there seems to be an irreducible difference in processing ability as well.

At the other extreme, two adults with left hemispherectomy (performed to remove tumors developed during adulthood) revealed extremely poor verbal ability, but not its complete lack (McFie, 1961). Between the age of one year and some unknown upper limit, the brain seems to keep some of its initial plasticity, allowing each hemisphere to develop abilities for which it is normally not very proficient (McFie, 1961). The two patients just described (Gott, 1973; Hillier, 1954) were probably still in this phase.

A thorough examination of the linguistic abilities of the left and right hemispheres has been undertaken by Dennis and her colleagues (Dennis, 1980b; Dennis, Lovett, & Wiegel-Crump, 1981; Dennis & Whitaker, 1976) on one case of right hemidecortication and two cases of left hemidecortication, performed before the age of 5 months. The examinations published to date took place when the children were between 9 and 14 years old. One fascinating finding of these studies is that equal performances in decoding written words can be mediated by different mental representations. The child retaining his left hemisphere shows a good awareness of the phonological structure of language: His reading draws on morphophonological properties of English orthography, and he reveals a tacit knowledge of rules that map writing onto speech when he reads new or unfamiliar words. None of these abilities is displayed by the two children retaining their right hemispheres. Yet with known words, their reading performance is equivalent to that of the child retaining his left hemisphere. Only with unknown words does their performance disintegrate; this shows that their word knowledge is not based on a morphophonological representation, so that they cannot exploit English orthographical principles to decode new words. These findings are remarkably well in line with the ideas developed by Mattingly (1972, 1984) concerning the relation between proficient reading and the availability of morphophonological representations of words in the mental lexicon. This author has also stressed that spoken language comprehension is probably less dependent on the existence of such representations than is reading (Mattingly, 1984). This claim is supported by the failure of Dennis and Whitaker (1976) to demonstrate differences in the abilities of left and right hemidecorticate children in their ability to deal with the phonemic and semantic aspects of spoken language. We may also note that a capacity for syntactic processing was much greater in the child retaining his left hemisphere than in the other two children. This is consonant with other data mentioned earlier (Dennis, 1980a; Dennis & Kohn, 1975).

Conclusions

The most important point of this section is the contrast between the disintegration of calculation and arabic numeral reading caused by lesions in the language areas of the left hemisphere and the relative preservation of these abilities by patients showing a disconnection between intact language areas and the visual cortex.

The only point left for discussion is the interpretation of the better identification of arabic numerals than of letters by the 11 alexics without agraphia of Group 1, those for whom the presumption of a pure disconnection syndrome is most likely to be correct. All these patients had their language functions located in the left hemisphere, they did not display any known cerebral brain disorder before their alexia, and the syndrome was caused by brain lesions in adulthood. Hence, these patients are the best suited for the assessment of the ability of the right hemisphere to deal with visual symbols.

A first possible explanation of the better performance with arabic numerals than with letters is that it is simply easier to discriminate 1 visual symbol out of 10 possible visual configurations than 1 out of 26 possibilities. We find this extremely unlikely. Both sets of symbols have evolved from the need to allow efficient reading. They incontestably succeed in doing so, especially under the temporally unlimited viewing conditions typical of the neuropsychological examination.

Far more likely is that performance is determined by the extent to which the right hemisphere can process the meaning of different stimuli. In essence, this amounts to proposing exactly the same schema of interpretation as that used by Geschwind (1965) to explain the differential ability to name objects and colors. Remember that the two basic assumptions are that (a) only the left hemisphere can generate a naming response. and (b) although visual information reaching the right hemisphere cannot be transmitted to the left hemisphere because the splenial route is sectioned, the information can be transferred, once it has been given a semantic interpretation, through the anterior intact portion of the corpus callosum. Hence, the solution of the problem should be sought by analyzing the nature of the semantic information conveyed by letters and arabic numerals.

The meaning of a letter is determined by the phonological unit of the spoken language to which it refers and by its relation with other similar units. In other words, the meaning of a letter is defined in terms of properties that the right hemisphere is unable to process, even when it has developed an idiosyncratic language competence, due to complete loss of the left hemisphere (Dennis et al., 1981). A fortiori, a right hemisphere that has never faced the problem of associating sounds to letters should be even less able to extract their meaning. This entails that, beyond the untransmittable visual information, there is simply no other form of information that can be conveyed to the left hemisphere. In this vein, the very poor performance of alexics without agraphia in reading and understanding phonographically written words argues for the hypothesis that word recognition is mediated by letter or syllable (kana) recognition.

By contrast, arabic numerals have a meaning in a symbolic system that has nothing to do with phonology. There is therefore no reason why the right hemisphere could not generate a semantic representation of the digit and transfer it to the other side, a task it seems able to perform with objects as well. This explanation is consonant with the better ability of the right hemisphere to interpret kanji logograms than kana phonograms (Sasanuma, 1974b; Sugishita et al., 1978).

In concluding this section it is worth specifying the exact scope of the interpretation of the right hemisphere's better performance with arabic numerals than with letters. Arabic-numeral reading in alexia without agraphia is not always perfect, and this points to the fact that, though feasible, the task is nevertheless strained. The inefficiency of the procedure is also demonstrated by the fact that the reading of multidigit numbers is rarely preserved. This would not be the case if transmission of the component numerals to the left hemisphere were more efficient. At present, we do not know whether the poor naming performance is caused by inadequacy of the semantic representation generated in the right hemisphere, or by the poor ability of the corpus callosum in transmitting interpreted rather than raw sensory information, or both. A final point worth emphasizing is that although we may conclude from the performance of brain-damaged patients that the right hemisphere has some ability to process arabic numerals, we may not conclude that it is superior to the left hemisphere in doing so.

SUMMARY AND CONCLUSIONS

Let us take the different points in the reverse order to their presentation in the chapter.

1. With respect to brain-injured patients, the fact that (a) number processing is strongly, but perhaps not fully, dependent on the integrity of the language areas of the left hemisphere and (b) these areas can be disconnected from the visual information reaching the right hemisphere allows us to assess the differential ability of this hemisphere to deal with various surface forms of numbers and of other types of visual information. Hemifield presentation of stimuli is a useful technique in this framework. An understanding of how the information is processed will require both the general progress of the analytical power of cognitive psychology as a whole and the comprehension of the basic modes of processing of each hemisphere in particular.

2. As for lateral hemifield presentation of stimuli to normal subjects, we may doubt whether the technique will help us to achieve either or both of the requirements just mentioned, at least insofar as one adopts a multicomponential view of processing. The analysis of the problem presented at the end of the third section is, of course, not the only one possible. However, it is based on the simplest and most tractable view of processing we have, and this casts serious doubt on the ability of the approach to fare better in more complex theoretical frameworks. The results show a RVF advantage for both logographic and phonographic number representations. Whether this pattern of results should be considered at odds with claims for a LVF advantage in the processing of logograms in general depends on the validity of this assertion, which is still controversial.

3. As regards numerical size comparison judgments, two of the basic effects—symbolic distance and serial position—were found to be independent of the surface form of the stimuli in experiments published to date. By inference from related data we hypothesized that such will also prove to be the case for a third effect—semantic congruity—for which the information is still lacking. The Stroop-like task leading to a size congruity effect has been judged too complicated to provide useful, nonparadigm-bound information, a conclusion that extends to hemifield presentations for the reasons just invoked. The strategy of research illustrated in this approach could, of course, be extended to cover a variety of questions about the basic knowledge associated with single-digit numbers. One can, for instance, use the same paradigm in comparison judgments related to the odd versus even, prime versus nonprime, multiple of two versus nonmultiple of two questions. The task need not be an explicit comparison between two numbers; it can also take the form of judging whether a single number possesses the property under investigation.

4. Three points should be made about the discussion of number representations.

First, concerning multidigit number processing, it seems appropriate to distinguish between arabic numerals and number names irrespective of the surface form of the latter. The facts that arabic numerals belong to a different, more abstract notational system and that they are also intimately bound to mathematical activities make them a priori distinct from number names. The irrelevance of the surface form can be further emphasized by predicting that Japanese (or Chinese) aphasics would show the same difficulty in transcoding multidigit numbers written in one logographic form into another logographic form (arabic numerals into kanji words and vice versa) as occidental aphasics have in transcoding these same numbers represented logographically (arabic numerals) into alphabetically written number names, and vice versa (Deloche & Seron, 1982; Seron & Deloche, 1984).

Second, as soon as one focuses on the processing of single-digit numbers, the characteristics of the notational system of which the number representations are the elements cease to play a prominent role, whereas the nature of the surface form of the numbers now becomes the important variable. We should expect that access to the stored knowledge associated with these elements would be influenced by factors affecting the reading of any kind of word. From this point of view it is, therefore, appropriate to regroup the symbols into a logographic and a phonographic category, irrespective of the underlying notational system. With normal subjects, we expect the surface form of the number to affect the speed with which their conceptual knowledge is accessed, but we expect the characteristics of this knowledge, as revealed by the pattern of interactions between different variables, to be the same irrespective of the surface form of the numbers. As far as the available evidence goes, this belief is not yet contradicted (cf. conclusion 3).

Third, single-digit number processing by adult brain-injured people could lead to a more complex picture. One should consider two cases. If, on the one hand, the language areas of the left hemisphere are intact, but disconnected from the visual cortex (ideal cases of alexia without agraphia or LVF presentations with section of the splenium of the corpus callosum), the right intact hemisphere could translate the visual numbers into interpreted representations transmissible to the left hemisphere, provided the numbers are represented logographically (one should also allow for the possibility that the right hemisphere may learn to process the small set of phonographic numbers as if they were logograms). In this case, a task could be performed according to the normal synergic activity of the hemispheres of an intact brain, leading to a performance qualitatively equivalent to that of normal subjects, save for some eventual loss in efficiency. If, on the other hand, the language areas of the left hemisphere are injured and if the task can be performed at all, then performance should be at least partially determined by right hemisphere competence in dealing with numbers. A performance qualitatively different from that of normal subjects could then be considered an index of the idiosyncracy of the right hemisphere's knowledge of numbers. The nature of the right hemisphere competence could then be studied in commissurotomized patients, provided the cognitive capacities of the right hemisphere of these severely epileptic people could be considered representative of those of normal subjects.

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