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Continuous versus discrete information processing: evidence from movement-related potentials

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Introduction

The question of the nature of communication among elements of the human information processing system is critical for theories of human cognition (Miller 1988, this volume). In this paper, we will argue that evidence from measures of movement-related brain potentials suggests that communication does not always take place in a single, discrete, all-or-none fashion. We will focus particularly on the communication between that part of the system responsible for the evaluation of stimulus information and that responsible for the preparation and execution of overt motor responses. There appear to be situations in which partial information about a stimulus is transmitted to the response system before the stimulus has been completely evaluated. As we shall see, such data are consistent with the idea of a continuous flow of information between stimulus evaluation and response activation systems. However, they are also consistent with the kind of multiple discrete model proposed by Miller (1982).

There are also situations in which information appears to be transmitted in an all-or-none fashion. The fact that the mode of communication is not always the same raises questions as to the factors that determine whether and when communication will be discrete or multiply discrete or continuous. In the last part of this paper, we will consider some possible explanations for the variability in communication and we will present some preliminary data that point to the role of strategies.

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The human information processing system

We assume that human information processing takes place in a number of distinguishable stages, each of which performs a specific function involving the transformation of information. The stages are assumed to be contingent such that the operations performed by 1 stage depend on the output of some antecedent stage, although this contingency does not imply (as some models assume) that information transmission always takes place in a single discrete 'chunk.' For our purposes, it is sufficient to conceive of 2 major stages – a stage responsible for evaluation of the stimulus and a stage responsible for preparation and execution of responses. We label these superstages 'stimulus evaluation' and 'response activation,' respectively.

Miller (1988, this volume) has proposed that there are 3 senses in which processing in the human cognitive system may be said to be discrete or continuous: input representation, transformation, and transmission. In this paper, we will focus on only one: information *transmission*.

Furthermore, as Miller has argued, the discrete-continuous dichotomy may be an oversimplification. It is more fruitful to consider a discrete-continuous *dimension*, with intermediate levels that are neither fully continuous nor fully discrete but multiply discrete.

Early communication

Within the framework proposed by Miller, then, our interest is in the question of information *transmission* – that is, on the question of communication between stimulus evaluation and response activation systems. Specifically, we want to know if the stimulus evaluation system passes along information to the response activation system in a single chunk. Or is there transmission of partial information such that responses are activated before stimulus evaluation is completed?

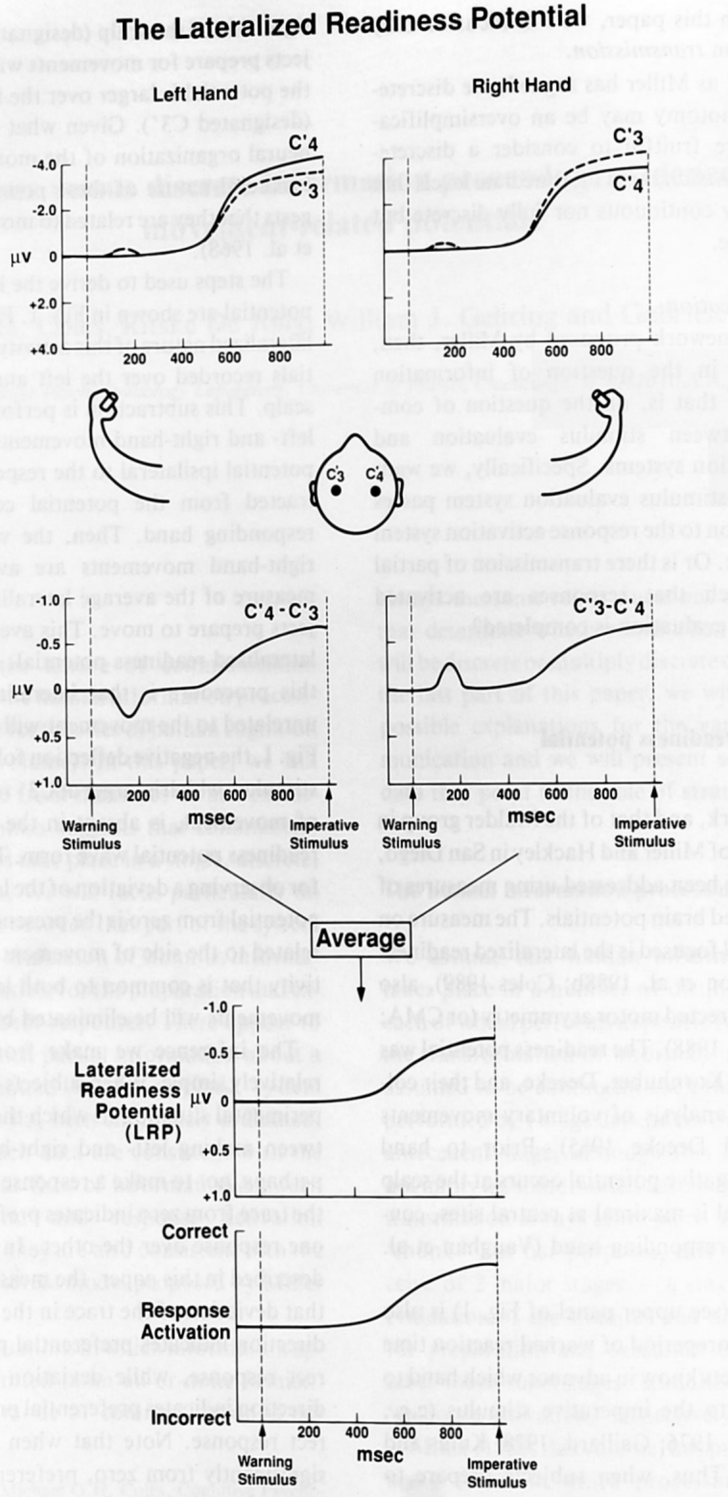
The lateralized readiness potential

In our recent work, and that of the Mulder group in Groningen, and of Miller and Hackley in San Diego, these issues have been addressed using measures of movement-related brain potentials. The measure on which we have all focused is the lateralized readiness potential (Gratton et al. 1988b; Coles 1989), also referred to as corrected motor asymmetry (or CMA; see De Jong et al. 1988). The readiness potential was first observed by Kornhuber, Deecke, and their colleagues in their analysis of voluntary movements (Kornhuber and Deecke 1965). Prior to hand movements, a negative potential occurs at the scalp and this potential is maximal at central sites, contralateral to the responding hand (Vaughan et al. 1968).

The potential (see upper panel of Fig. 1) is also observed in the foreperiod of warned reaction time tasks when subjects know in advance which hand to use in response to the imperative stimulus (e.g., Rohrbaugh et al. 1976; Gaillard, 1978; Kutas and Donchin 1980). Thus, when subjects prepare to move their left hand, the negativity is larger over the right side of the scalp (designated C4′). When subjects prepare for movements with their right hands, the potential is larger over the left side of the scalp (designated C3′). Given what we know about the neural organization of the motor system, the contralateral nature of these potentials certainly suggests that they are related to motor action (Vaughan et al. 1968).

The steps used to derive the lateralized readiness potential are shown in Fig. 1. First, to illustrate the lateralized nature of this activity, we subtract potentials recorded over the left and right sides of the scalp. This subtraction is performed separately for left- and right-hand movements. In each case, the potential ipsilateral to the responding hand is subtracted from the potential contralateral to the responding hand. Then, the values for left- and right-hand movements are averaged to yield a measure of the average lateralized activity as subjects prepare to move. This average measure is the lateralized readiness potential. A critical aspect of this procedure is that lateralized activity that is unrelated to the movement will average to zero. In Fig. 1, the negative deflection following the warning stimulus, which is larger at C3′ regardless of the side of movement, is absent in the derived lateralized readiness potential wave form. Thus, the only basis for observing a deviation of the lateralized readiness potential from zero is the presence of activity that is related to the side of movement. Asymmetrical activity that is common to both left- and right-hand movements will be eliminated by the averaging.

The inference we make from this measure is relatively simple. When subjects are placed in an experimental situation in which they must choose between making left- and right-hand responses or, perhaps, not to make a response at all, deviation of the trace from zero indicates preferential priming of one response over the other. In the research to be described in this paper, the measure is derived such that deviation of the trace in the upward (negative) direction indicates preferential priming of the correct response, while deviation in the downward direction indicates preferential priming of the incorrect response. Note that when the trace deviates significantly from zero, preferential priming must have taken place by that point in time.



g. 1. Derivation of the lateralized readiness potential. See text for details. (Copyright 1989, Society for Psychophysiological Research. Reprinted with permission from the publisher.)

Multi-attribute stimuli and information transmission

Measures of the lateralized readiness potential have been used in a variety of different paradigms all of which involve stimuli that have 2 response-relevant attributes (see Table I). In each case, stimuli are selected so that information about one attribute can be processed faster than information about the other attribute. For ease of presentation, we will refer to these attributes as attribute 1 and attribute 2, respectively. The question is whether information about attribute 1 can be used to prepare responses before information about attribute 2 is available. If so, then we infer that transmission is continuous or multiply discrete; if not, then information is transmitted in an all-or-none fashion.

Various assignments have been used to link stimulus attributes to responses. In the conflict paradigm, attribute 1 is sometimes associated with the incorrect response. Thus, early communication should result in early activation of the incorrect response. In the go/no-go paradigm, attribute 1 provides information about *which* response should be made, while attribute 2 indicates *whether* a response should be made. In this case, early communication should result in early activation of a response even on no-go trials. Finally, in the congruence paradigm, attribute 1 sometimes provides information that can be used to prepare the correct response hand, while the particular finger to be used is specified by attribute 2. In this case, early communication should result in early activation of the correct response hand.

The conflict paradigm

(a) Noise-compatibility. In the noise compatibility paradigm (see Gratton et al. 1988a; Smid et al. 1990), subjects must make a right- or left-hand response as a function of the center letter in a 5 letter array. On compatible trials, the center letter is flanked by replications of the same letter; on incompatible trials, the center letter is flanked by letters associated with the other response. For our purposes, the letter arrays have 2 attributes – first, the identities of the letters in the array without regard to their locations; second, the identity of the letter at the central target location. On the basis of previous research, we have reason to believe that information about letter identities is available before information about the identity of the central target letter. Thus, if early communication occurs, responses should be activated on the basis of the identities of all the letters in the array. Of course, on incompatible trials, this should lead to activation of the incorrect response, since 4 of the 5 letters in the array are associated with the incorrect response.

Data obtained both by us (Gratton et al. 1988a) and by Smid et al. (1990) demonstrate that early communication occurs in this paradigm. For incompatible trials, there is a significant dip in the lateralized readiness potential indicating preferen-

TABLE I

Paradigm	Attribute 1	Attribute 2	Early communication	Reference
Noise-compatibility	Letters' identities	Letter at target location	Yes	Gratton et al. (1988)
Noise-compatibility	Letters' identities	Letter at target location	Yes	Smid et al. (1990)
Rhyme judgment	Orthography	Phonology	Yes[a]	Coles et al. (1988)
Sentence verification	Semantic relatedness	Propositional value	?[b, c]	Gehring et al. (1990)
Go/no-go	Letter name (shape)	Letter size	Yes	Miller and Hackley (1990)
Go/no-go	Spatial location	Character identity	Yes	Osman et al. (1988)
Selective attention/ memory search	Color	Letter identity/memory set membership	No[b]	Wijers et al. (1989)
Congruence (Miller)	Letter name (shape)	Letter size	No	De Jong et al. (1988)

[a] Effect in predicted direction but not significant.
[b] Response hand assignments were alternated in different trial blocks.
[c] Overt behavioral measures suggest that early communication occurs (see text).

tial activation of the incorrect response. This dip is followed by activation and subsequent execution of the correct response.

(b) Rhyme judgment. In this experiment, the task of the subject is to indicate whether 2 words, presented on a screen, do or do not rhyme. For our purposes, the words may be considered to have 2 attributes: their orthography (the way they look) and their phonology (the way they sound). Information about orthography is apparently available before information about phonology. As with the noise-compatibility paradigm, the attributes of the word pairs are sometimes compatible and sometimes incompatible. For compatible word pairs, processing of orthography and phonology converge as in the case of *cook-book* and *table-soap*. For incompatible word pairs, orthography and phonology conflict as in the case of *dough-flow* (words that rhyme but do not look alike) and *dove-move* (words that look alike but do not rhyme). If early communication occurs, and information about orthography is used to activate responses before information about phonology is available, then we should again see a dip in the lateralized readiness potential on incompatible trials.

The data from this experiment were suggestive (see Coles et al. 1988). A dip was indeed evident for conflict trials. However, possibly because the effect is small, and only a limited number of trials were available, the dip was not significantly different from zero.

(c) Sentence verification. In this task (Gehring et al. 1990), subjects must determine the truth or falsity of sentences of the form 'all cows are animals' or 'all flowers are roses' or 'all cows are flowers.' In fact, only word pairs, consisting of subject and predicate, are presented. The subject is instructed to interpolate the other words in the sentence.

Meyer (1970) and others have proposed that sentence verification consists of at least 2 stages that process 2 different attributes of the sentence: first, the relatedness of the subject and predicate of the sentence, and second, the propositional value, or truth, of the sentence. In the processing system proposed by some theorists (e.g., Smith et al. 1974), it is assumed that relatedness is used as an indication of the truth of the sentence. For this reason, relatedness and propositional value may be compatible as in the cases of 'all cows are animals' (related and true) and 'all cows are flowers' (unrelated and false), but they may also be incompatible as in the case of 'all flowers are roses' (related and false). This sentence presents a conflict because flowers and roses are semantically related, but the sentence is false. As with other instances of the conflict paradigm, we expect to see the dip in the lateralization function for conflict sentences if information about semantic relatedness is communicated to the response activation system before the truth of the sentence is established.

Results of preliminary analyses of the data from this experiment are equivocal. On the one hand, there is no evidence in the grand average wave forms of early communication for conflict sentences – that is, there is no evidence of a significant deviation below zero on conflict trials. However, for some subjects, behavioral data point to an influence of the semantic relatedness of subject and predicate on response accuracy and latency. In particular, on conflict trials, accuracy is below chance (50%) for fast responses. These behavioral data are consistent with conclusions reached by Ratcliff and McKoon (1982) and by Kounios et al. (1987). However, more research is needed to resolve the apparent conflict between the behavioral and psychophysiological data (see also below).

The go/no-go paradigm

In the go/no-go paradigm, the stimulus again has 2 attributes. However, in this case, one attribute indicates *which* of 2 possible responses should be made, while the other attribute informs the subject *whether or not* a response should be made. Two variants of the paradigm have been used, one by Miller and Hackley (1990), the other by Osman and his colleagues (Osman et al. 1988).

In the Miller and Hackley experiment, the stimuli could be large or small versions of the letters S or T. Subjects were instructed to respond with their left or right hands to an S or T of one size, but to withhold their response if the letter was of a different size.

Because the shape of the letters was easier to discern than their size, information about letter shape could be available before information about letter size. In this case, then, early communication would be suggested by the presence of response activation on no-go trials. Such an inference would be strengthened if Miller and Hackley had varied the discriminability of the go/no-go stimulus (c.f., Osman et al. 1988). This manipulation is critical if one is to demonstrate that early signs of response activation evident in the lateralized readiness potential are the product of early communication rather than hierarchical response selection strategies (c.f., De Jong et al. 1988).

In the Osman et al. (1988) version of the experiment, the stimuli were either letters or digits presented to the left or right of fixation. If the stimulus was a letter, subjects had to respond with their left or right hand as a function of the spatial location of the letter. Alternatively, if the stimulus was a digit, the response had to be withheld. Because the spatial location of the stimulus was easier to discern than its identity, information about location was available before information about identity. Thus, early communication would be evident if responses were initiated on no-go trials.

In different trial blocks, Osman et al. (1988) also varied the difficulty of the letter/digit discrimination. In the easy condition, the letter was V and the digit was 5. In the hard condition, the letter was l and the digit was 1.

The lateralized readiness potential data for both experiments revealed that responses were activated on no-go trials. In the Miller and Hackley case, information about letter shape was apparently used to prime responses before information about letter size was available. In the Osman et al. experiment, information about spatial location was evidently used to prime responses before information about stimulus identity was available. Regardless of the difficulty of the letter/digit discrimination, the lateralized readiness potential began to deviate from zero at about the same time. However, the process was aborted sooner when the discrimination was easier.

Taken together, these 2 experiments provide evidence for the use of partial information to prime responses.

Selective attention and memory search

The paradigm devised by Wijers and his colleagues (Wijers et al. 1989; Mulder and Wijers, this volume) combines the Sternberg memory search task with a selective attention component. It bears some similarity to the go/no-go paradigm in that subjects are required to respond only if a certain configuration of stimulus attributes is present.

Before each block of trials, subjects had to memorize a set of letters consisting of either 1 or 4 items. These items constituted the targets. Targets and non-targets (letters not in the memory set) were presented visually in 1 of 2 colors and the subjects were required to respond only when a target item was presented in a pre-designated relevant color. Color, therefore, served as a selection cue and defined whether or not the letters should be attended. Responding hand was varied between trial blocks.

There were several kinds of displays: those that contained a target in the relevant, to-be-attended, color; those that contained a non-target in the to-be-attended relevant color, those that contained a target in the unattended color, and those that contained a non-target in the unattended color. If color is processed first, then one might expect color information to be used to activate responses before letter identity and target status are established. Thus, early communication might be evident in the lateralized readiness potential wave forms whenever the display contained a letter in the attended color, regardless of the target status of the letter. As information about letter identity and memory set membership became available, the response would be aborted if the letter turned out to be a non-target.

In fact, the data failed to provide any evidence for early communication. While the lateralized readiness potential was clearly evident for displays containing a target in the attended color, there was no sign of any systematic activity when a non-target was presented in the attended color. Thus, in contrast to the preceding studies involving the go/no-go paradigm, the present experiment suggests that subjects do not, in fact, use partial information about a multi-attribute stimulus to prime responses.

The congruence (Miller) paradigm

This paradigm differs from those described previously in that subjects are required to execute 1 of 4 possible responses as a function of the stimulus. The 4 responses involve the index and middle fingers of the left and right hands. These 4 responses are associated with the size and identity of a letter stimulus. In the experiment by De Jong and colleagues (De Jong et al. 1988), the stimuli could be either the letter N or the letter S and these letters could be either large or small. Possible letter sizes were deliberately adjusted so that letter size was more difficult to determine than letter identity.

In different conditions, the 2 attributes of the stimulus were linked to either the finger or the hand dimension of the response set. In the hand:size condition, letter size was the cue for the response hand, while in the hand:name condition, letter identity cued the hand. In the latter case, it was assumed that subjects might use letter identity to activate their responding hand before they had determined letter size, that is, before they knew which finger to use. This assumption leads to the prediction that early activation of responses should be evident in the lateralized readiness potential when responding hand is cued by letter identity. In fact, the data indicate that the development of the lateralized readiness potential did not occur earlier in this condition than when the response hand was cued by the less discriminable letter size.

In this paradigm, then, subjects do not appear to use partial information to prepare responses. Rather, as De Jong et al. (1988) propose, subjects appear to be biased towards a holistic processing mode in which both stimuli and responses are treated as distinct units rather than as a combination of dimensions.

Synthesis

From the examples just described we have seen that the motor system *can* be primed on the basis of preliminary information about the stimulus. Thus, communication between stimulus evaluation and response activation systems does not always take place in an all-or-none fashion.

The smooth appearance of the lateralized readiness potential wave forms is suggestive of a continuous transmission of information between stimulus evaluation and response activation systems. However, as with speed-accuracy trade-off functions, this smooth appearance may be misleading because of the averaging procedures used to derive the wave forms. In this case, averaging could obscure the fact that the underlying pattern of communication occurs in several discrete chunks, whose timing varies from trial to trial, with perhaps 1 discrete transmission for each response-related stimulus attribute. Furthermore, it could also be the case that the smoothly changing lateralized readiness potential reflects the early transmission of partial information followed by a gradual development of response preparation. Both these interpretations would be in line with Miller's asynchronous discrete coding model (Miller 1982).

As we have seen, to the extent that we believe the lateralized readiness potential data, early communication does not always occur. One possible reason for the apparent inconsistency in the mode of communication is that the different experiments reviewed above involve different stimuli. It might be the case, then, that particular stimuli lend themselves to be processed in chunks and for the results of this processing to be communicated to the response system in chunks. However, this explanation is not plausible because experiments using very similar stimuli have found evidence both for and against early communication. De Jong et al. (1988) used letter stimuli that varied as a function of letter name and letter size and found that partial information about letter name was not used to prime responses. However, Miller and Hackley (1990) used the same type of stimuli and found that responses *were* primed on the basis of letter name information. Thus, it appears that the mode of communication depends on task requirements, rather than the particular stimuli used. In particular, in the De Jong et al. experiment, subjects had to execute 1 of 4 possible responses on any trial, while in the Miller and Hackley study subjects performed a 2-choice go/no-go task. In the latter study, subjects appear to have adopted a hierarchical response selection strategy (first select response hand, then make a go/no-go decision), while in the former study subjects were apparently biased towards a more 'holistic' response selection strategy (see De Jong et al. 1988). This is an example of how different task requirements may lead subjects to adopt different processing strategies, with the mode of communication being dependent on strategies. We will develop this argument below.

A second possible reason for the inconsistency in the mode of communication concerns the relationship between certain experimental designs and the manner in which the lateralized readiness potential is computed. Recall that wave forms for left- and right-hand responses must be averaged to eliminate lateralized activity that is unrelated to the movement. Thus, at different times in the experiment, each hand must be associated with the correct response for each condition. In most designs, this requirement is satisfied on different trials within a trial block. However, for the sentence verification task and the selective attention/memory search task, this requirement could only be satisfied by alternating response-hand assignments between trial blocks. For example, in the sentence verification task, in some trial blocks, the right hand would be associated with the 'true' response and, in other trial blocks, with the 'false' response. While subjects are quite able to change response-hand assignments in this way, it may be that such a change leads subjects to adopt a conservative strategy that downplays the role of partial information. In addition, in the selective attention/memory search study, only 1 response was ever required of the subjects in a given block of trials (subjects either responded or withheld the response following stimulus presentation). Under these conditions, subjects might be expected to maintain a constant state of response hand readiness (and, therefore, a constant level of lateralization of the readiness potential) *throughout* the trial block.

Taken as a whole, these arguments point to a role of subject strategy as a reason for the fact that partial information is not consistently used to prime responses. As a working hypothesis, we propose that partial information will only be used to the extent that early communication between stimulus evaluation and response activation systems has utility in the context of task goals (see De Jong et al. 1988). This idea of utility carries with it the notion that the subject has at least some control over the use of partial information and that, in exercising strategic options in task performance, the subject may or may not use the information.

The role of strategies

In a recent series of studies (Gratton et al. 1988a), we have begun to explore these ideas in the context of the noise-compatibility paradigm. In particular, we have examined the possibility that variations in the probability of compatible and incompatible noise are associated with variations in the probability that partial information will be used to execute fast and accurate responses. The argument goes like this: when the noise is compatible with the target, fast and accurate responses can be based on the noise letters and there is no need for subjects to wait until they know the target letter before responding. Thus, when subjects are in a situation in which compatible noise trials are probable, a strategy that emphasizes the use of partial information should be useful. Conversely, when incompatible noise trials are probable, a strategy based on the use of partial information will give inaccurate responses. In this case, subjects should reject such a strategy and not allow responses to be primed on the basis of preliminary stimulus evaluation.

We have examined these ideas in 2 experiments – in both cases using the lateralized readiness potential to monitor the use of partial information. In the first of these experiments, we looked at subjective probability effects by examining the effects of noise as a function of the compatibility of the noise on the preceding trial. The idea here was that subjects would tend to use partial information if such a strategy would have been effective on the preceding trial. In the second experiment, the probability of compatible and incompatible noise varied between trial blocks. The idea here was that, when compatible noise is likely, the subjects should adopt a strategy based on partial information[1].

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[1] It is possible that, when incompatible trials are likely, subjects can use the fact that there is a correlation between noise letters and target letter to select the correct response (see Logan 1985). In this case, they would have to transform the partial information (that is actually associated with the incorrect response) and use it to prepare the correct response. If such a strategy was used when the probability of incompatible noise is high, then subjects should be faster to respond on incompatible than on compatible trials. This is because the transformation strategy would lead to the incorrect response on compatible trials. This result was not, in fact, obtained (see below). Thus, it appears that subjects did not use this transformation strategy in our experiments.

Behavioral data from these experiments suggested that the effect of noise depended on both subjective and global probability of compatible noise.

The noise effect on reaction time and accuracy was larger when the subjective or global probability of compatible noise was high. Thus, the behavioral data support the idea that overt responses were more influenced by partial information about the noise letters in the array to the extent that this information could be used to guide fast and accurate responses.

This inference was supported by the lateralized readiness potential data. Difference wave forms were obtained by subtracting the wave forms for incompatible trials from those for compatible trials. Conceptually, this gives us a wave form that summarizes the overall effect of noise on the lateralized readiness potential. In both experiments, this effect of noise was larger when compatible noise was probable.

These experiments provide preliminary support for the idea that the mode of communication between stimulus evaluation and response activation is modifiable. At present, we cannot prove that this modification occurs as a result of the activities of some kind of central supervisory system, rather than because of a more peripheral mechanism involving the use of specific stimulus-response connections. This issue will be the subject of future research. However, whatever the mechanism responsible, the data support the idea that the use of partial information depends on the task situation. More important, our general view that the connection between stimulus and response can vary renders the feud between continuous flow-ers and discrete stagers quite vacuous. Instead of asking the question, 'is communication continuous or discrete?,' we should ask 'when and why is communication continuous or discrete?'

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