Introduction

How continuous are discrete notions of human information processing?

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Reaction time is probably the most popular and widely used method in Experimental Psychology. This of no surprise if we realize that most cognitive processes occur in hundreds of ms or at least a few seconds. One of the most persistent reasons for using the method has been the drive of the experimental psychologist to uncover the nature and working of the sensory, cognitive and motor processes that contribute to the complex outcome that we call human performance. Looking back at a century and a quarter of psychological experiments it is safe to say that one of most seminal contributions in the field have been the transcript of Donders lecture to the Dutch Royal Academy of Sciences held in 1868 (Donders, 1869) in which he presented his version of the subtraction method for the decomposition of the processing stages that make up reaction time. It is even well known that the centennial anniversary of Donders’ publication was celebrated with a symposium organized by the Attention and Performance Foundation. The contributions to that conference were published in Acta Psychologica (Koster, 1969), the same journal that published follow ups of that conference in 1990 (Stoffels et al., 1990) and in the present volume. A second milestone undoubtedly is the influential contribution of Saul Sternberg (1969) at the Attention and Performance II, where he introduced the modern version of Donders decomposition logic, namely the additive factor method. It is perhaps accidental but still interesting to note that all the above mentioned publications were forthcoming in the Netherlands. The editors of the present volume greatly acknowledge the journal for opening its pages for the intricacies of reaction time processes again.

This special volume of Acta Psychologica contains contributions delivered at a meeting sponsored by the Dutch Royal Academy of Sciences (KNAW). It was organized by Gijsbertus Mulder (University of Groningen) and Andries Sanders.
The 1994 symposium concentrated on two related and leading questions:
1. To what extent and under what conditions is it warranted to portray human information processing as either the product of a typically continuous or a discrete or perhaps a more hybrid functional architecture?
2. How can additive factor method contribute to the discovery of processing stages (modules) that form meaningful elements for our understanding of that functional architecture?

With respect to the first question Miller (1988) pointed out that when posing the question of discreteness versus continuity of processing stages and information transmission, reflection on the concept of the grain size of information processing is a necessary condition to make further progress. At one extreme, a process could shift abruptly between two states and the process would be typically discrete. At the other one extreme, a process under consideration may consist of an infinite number of intermediate states. In the latter case we would be inclined to name the process fully continuous. Between these two extreme positions, intermediate positions may be adopted. The actual grain size chosen determines whether processing looks more continuous or more discrete. It is important to realize therefore that the grain size of any information processing model is the minimum size of the differences between possible model states. In other words, the distinction between possible models is quantitative rather than qualitative.

Another important distinction made by Miller is whether models deal with representations of stage input, with transformations within a processing stage, with the transmission of stage output to subsequent stages, or a combination.

In fact Miller showed that there exists a space of possible models and the task of research and theory is to provide us with evidence which model is most plausible in a particular case. By now, eight years after Miller's important theoretical article the truth of that statement becomes more clear as ever. It is a perfect description of the spirit of the conference on which the present volumes reports.

The general conclusion of the papers presented in this volume is that the question: "Is Human Information Processing Discrete or Continuous?" is, in its current formulation, an outworn and a too generally formulated issue. The answer simply is that it depends. One problem is that RT is itself a discrete index of processing. The transmission of small quanta of data from one process to another may be not be observed and as a consequence (and erroneously) discrete processing is inferred. Similarly other discrete responses such as saccadic eye movements may be similar in this respect. For that reason there is an increasing interest in more continuous measures of human information processing. In a substantial number of contributions to this volume the measurement of Event Related Brain Potentials is used in addition to RT. In this respect the LRP, an index of selective motor activation, and the EMG become almost indispensable in unravelling the
motor part of the reaction process. But even if more continuous measures are used the conclusion must be that the nature of human information processing depends very much on the nature of the task, the amount of practice, the strategy of processing and perhaps the type of measurement also. This implies for the future that theory and research has to develop tools that analyze the right model for a particular task under particular circumstances.

To help the reader in structuring the different aspects of the central topic, the contributions to the volume are grouped in three major categories. Their headings are the following:

I. Contributions centered around questions of discrete or continuous cognitive architectures and methods.

II. Contributions on discrete or continuous representations.

III. Articles on discrete or continuous models of motor control.

It should be admitted at the same time that the categorization is somewhat arbitrary because many articles are relevant for more than one of the issues mentioned below. We shall give a short description of each of the contributions and indicate how far mutual support in the different articles can be found.

I. Discrete versus continuous cognitive architectures and methods

Jeff Miller opens the volume in examining various and modified versions of the classical cascade model, which is known to violate the crucial assumption of discrete stage models. Deterministic versions grew at fixed rates to a fixed threshold. In the stochastic version the response criterium varies from trial to trial. One of the major findings of that analysis is that additivity of factor effects on mean RT is compatible with discrete stage models and cascade models and with a variety of overlapping stage models with different grow functions. So factor additivity per se does not support discreetness, and other tests are needed to arrive at such a conclusion. Nevertheless the additive factor method (AFM) remains a useful heuristic logic even if the underlying processing system does have a discrete architecture.

Ridderinkhof and Van der Molen investigate the usefulness of the additive factor method in situations in which multi-element stimuli contain relevant and irrelevant elements. The experimental factors are Target Size and symbolic S–R Compatibility, factors that would affect independent stages. The authors state that an important assumption of AFM is that the output of one stage to its successor is constant and that the time necessary to complete processing in a given stage is independent of the duration of processing in any preceding stage (the stage robustness criterium). Neither a discrete nor a continuous flow model is sufficient to explain their data and, therefore, a dual route-process architecture is proposed.
Dutta et al. raise the question whether the AFM is still valid in dual task situations. The authors discuss a dual-task consisting of memory scanning and mental arithmetic with digits as stimuli. When the same digit is relevant for both tasks cross-talk is observed. The size of the selective factors under these conditions is however much larger. Nevertheless the processing order mandated by the instructions was sometimes violated. The authors draw attention to the role of control process in cognitive architectures.

The paper by Mulder et al. concerns the role of neuroimaging in the discovery of processing stages. Components in Event Related Brain Potentials (ERP's) appear to show in real time the behavior of perceptual processing stages, like preprocessing and feature extraction, and cognitive and motor processing. The time resolution is very high and the selective effects of attention on these processes can be established. Methods based on changes in regional cerebral bloodflow (rCBF) show that in selective attention tasks at least nine brain systems (modules, or stages) are active. Memory and visual search activate at least four different brain areas, partly related to the different slave systems of Baddeley's working memory model. These data also indicate the distributed nature of processing systems. The authors also draw attention to the role of general control mechanisms in processing architectures. Probably the anterior cingulate plays a central role in these control processes.

Requin and Riehle record single neuron activity in monkey primary motor cortex in Go and No-Go trials. Multidimensional stimuli are used and stimulus response compatibility is also varied. The experiments provide evidence for partial transmission of information from visual to motor stages. However, Requin and Riehle also draw attention to the distributed nature of processing. The motor cortex contains sensory, sensorimotor and motor neurons. The classical view that the motor cortex is only specialized as a motor processor, i.e. only specialized for preparing and executing movements, is false. It is quite conceivable that the 'motor' cortex is still involved in further perceptual processing and as a consequence the observed partial information transfer could be consistent with a discrete processing model as well.

Smulders et al. attempt to augment mental chronometry by using in addition to RT, the latency of P300, an index believed to reflect the time of nonmotoric processing, and of the Lateralized Readiness Potential (LRP), an index believed to index selective motor activation. Stimulus degradation affects the latency of these components, response complexity does not affect the latency of P300 nor the onset latency of the LRP. Response complexity, on the other hand, affects the interval between the LRP onset and the response. These data nicely support temporal selectivity of factor effects. The onset of the LRP seems to occur during or shortly after response selection but preceding to motor programming. Response selection might be the function of the sensorimotor neurons discussed by Requin and Riehle (see above).

Osman et al. describe attempts to bisection RT with the LRP. In particular the authors wish to localize the effects of informative and noninformative precues. The informative precues that they used reduce response uncertainty. In addition to RT
and LRP onset, they also measured P300 latency onset, electromyographic onset, the LRP-RT interval and the interval between the imperative signal and LRP onset. Informative cues reduced RT, P300 latency and the signal-LRP interval, but the timing of EMG activity relative to RT remained the same. However, precues affected also the LRP-RT interval. Osman et al. propose different architectures to interpret the processes between the imperative signal and the LRP and between LRP and RT. The component processes can be characterized as nonmotoric and motoric and they could be serial or partly overlapping. Before definitive conclusions can be drawn tasks should be designed to determine to what extent nonmotoric processes affect the LRP-RT interval.

Human performance is seldom perfect, and even when an overt response is correct it may be accompanied by partial error activity. Coles et al. review the evidence and the role of partial errors by analyzing the LRP, the electromyogram and response force. Correct responses accompanied with partial errors are in general slower than ‘clean’ correct responses. Partial errors are another indication of the role of partial information in the guidance of responses. However, partial errors are monitored and corrected because otherwise overt performance would be even less perfect than we usually observe. When subjects make errors in choice RT tasks, a distinct negative deflection, probably related to an error-monitoring process, can be observed in the ERP. This process is most likely to be implemented in the anterior cingulate cortex or supplementary motor area, see also confirming evidence provided by Mulder et al. (above).

Smid and Mulder make the important distinction between the availability of partial information, visible in stimulus selection ERP’s and the use of it, visible in the LRP and EMG onset and RT. Several factors affect availability, such as stimulus discriminability, separability of stimulus dimensions, stimulus probability, prior assignment and practice. Apparently, the use of partial information is dependent on its utility for goal achievement and on the difficulty of the stimulus–response translation process (see also de Jong, Proctor, and Eimer et al.). In general the combined study of both availability and use, under different experimental conditions is another method to elucidate the important role of control mechanisms and principles. Their data clearly indicate that a simple continuous flow conception is untenable. At least three different levels are involved: an early within-dimension selection stage of feature analysis, a central between-dimension selection stage of feature conjunction and a late selection stage. An asynchronous coding model of partial information transfer is most useful in explaining their data (see Miller, 1982).

Finally, Meyer et al. describe a new theoretical framework, the EPIC (Executive-Process/Interactive-Control) architecture. The architecture assumes specific modules devoted to perceptual, cognitive and motor processing (note that the review of Mulder et al. is organized around these three types of processors). Each perceptual processor operates asynchronously, in parallel with other components of the architecture. The cognitive processor has no immutable decision or response selection bottleneck per se. The three subcomponents (declarative working memory, production memory and production-rule interpretator) enable a high degree
of parallel processing. An important task of the EPIC's motor processors is to convert symbolic identities of selected responses to specific features that desired overt movements should have. Supervisory (control) functions coordinate tasks according to executive production rules. Modelling experimental data within EPIC, which is partly compatible with Miller's asynchronous discrete coding model, raise doubts about the existence of pervasive bottlenecks in the human information processing system. The extent to which processing may seem 'discrete' or 'continuous' can depend on control strategies that the subject adopts (a conclusion which is reached in various papers, e.g. Coles et al., Osman et al. and Smid and Mulder). In general the picture emerging from all these papers on architecture and transmission suggest that stages of processing can be identified with converging methodologies and that transmission can be more discrete or more continuous depending on the task under study and the nature of control.

II. Discrete or continuous representations

The next section of the volume is concerned with representation. Massaro and Cohen state that even the strongest advocates of discreteness would not claim that discrete processing is universal. There are many instances in which the outcome of identification is necessarily continuous or 'fuzzy'. The authors compare a discrete feature model versus the fuzzy logical model in the prediction of the distribution of ratings in a pattern recognition task (the distinction between spoken vowels). The latter model assumes that continuously-valued features are evaluated, integrated and matched against prototypical descriptions in memory, and that a response is based on the basis of the relative goodness-of-match. It appears that feature analysis and the identification stage can best be described in terms of a fuzzy logic model with sequential stages, but with a continuous output. Such a model needs not to be true for subsequent processing stages.

Sanders shows that incompletely processed perceptual dimensions do not necessarily affect discrete saccadic eye movements. The subject's task is to compare two stimuli subtending a visual angle of 45 degrees, in a same/different task. Fixation time at the left stimulus (TL), the saccadic time (TM) and the time from fixating the stimulus at the right (SR) to the response (TR) are measured. Two dimensional stimuli are used, differing in encoding time. The relevance of these dimensions was manipulated. TL indicates parallel and interference free encoding. However, TL was not affected by the presence of a slow and irrelevant dimension, supporting a discrete model.

Kounias and Smith move to representations in the cognitive processor and show that, with the speed/accuracy decomposition technique, insight in an anagram solution task is sudden and discrete. Again their results support earlier conclusions that pan-continuous theorizing (e.g. Rummelhart and McClelland, 1986) should be avoided.

The conclusion from the present reports is that at the level of the perceptual processor and in agreement with earlier papers, parallel and continuous processing
is evident, but that at the level of the cognitive processor discrete processing might occur as well.

### III. Discrete versus continuous models of motor control

The last section concentrates on the nature of processing at the motor side of the processing architecture. Levy and Pashler pose the interesting question whether perceptual processing continues during response selection and production. Speeded and unspeeded response accuracies are compared in a naming task in which stimuli are degraded. Perceptual analysis appears to continue during response processing, confirming evidence obtained with the LRP (see Coles et al. and Smid and Mulder). As already shown by Miller, the validity of the Additive Factor Method is not affected by this overlap in processing. The perceptual system continues working on the stimulus, the final decision might depend upon the amount of information crossing a distinct threshold. This is also true for saccadic eye movements as is shown by Irwin and Andrews. During saccadic eye movements information processing also continues. The interesting question is what type of information processing continues. The authors suggest that the automatic process of pathway activation does, while attended processes do not. Saccadic suppression is probably most wanted if tasks share processing structures and cross-talk is likely (see also Dutta et al.). In this context and already earlier dual-route models were proposed (Ridderinkhof and Van der Molen). This is also done by Proctor et al. They investigated whether response codes could be affected by relevant and irrelevant stimulus information. Well-known compatibility effects are probably mediated by an automatic, activation route. In addition de Jong argues that in visuo-manual aiming tasks information transmission from perceptual to motor processes takes place in a continuous fashion in ideomotor compatible tasks. A non-overlapping mode of operation is present in non-ideomotor compatible tasks requiring an S–R translation or response retrieval process. In that case a limited capacity and discrete operating process interferes (but see also Meyer et al. for an alternative explanation).

A dual route explanation of compatibility is adhered by Eimer et al. They conclude that the translation process does not protect responses or response codes from being activated (see also Proctor et al.). A direct route allowing automatic activation, is used if stimulus and response features overlap; an indirect route is used if S and R codes have to be linked in an arbitrary manner. The first lateralization phase of the LRP and its return to baseline is interpreted as electrophysiological evidence for the activation of and decay in the direct route. Also Heuer argues from computer simulation of the programming module (motor processor) that discrete transmission within this module is inconsistent with the experimental data on RR compatibility. Returning again to discrete aiming movements, Spijkers and Spellerberg provide evidence for a model of continuous on-line control of movement execution.

In conclusion, the last papers all allow continuous processing between the perceptual and the motor processor under specific task conditions. Discrete processing occurs if arbitrary perceptual and motor codes have to be connected.
References


