he thought, was involuntary and resulted from the passage of sensory information through the hollow nerves (a hydraulic piping system) to the brain where it was reflected out to the muscles to produce action. Because Descartes wished to reconcile his religious beliefs with his mechanistic view of behavior, he argued for the presence of a soul (the word *l'âme* means *mind* or *soul* in French). Following the ancient belief that we possess both spiritual and material elements, Descartes believed that all people possessed a free insubstantial soul and a mechanically operated body. While the body acted as a machine, the soul could direct the body through its effect upon the pineal gland in the center of the head. By moving the gland from side to side, the soul could open or close different neural passageways. This, in turn, would direct the movement of the "animal spirits" through the hollow nerves and ultimately produce action. Through the movement of the pineal gland, called the *conarium* or *seat of the will* by Descartes, the spiritualistic soul influenced the materialistic body (Boring 1957). In seventeenth-century information-processing terms, the soul was the external agent that directed and controlled sequences of behavior.

With slight modification, Broadbent's (1957) pipeline model of processing, the Y-shaped tube model with the flap at the branch of the Y, is similar in some respects to the earlier model of Descartes. In addition to the fact that both are hydraulic pipeline models, both models assume that choice is determined at a single point in the system by some form of higher control or "higher controller" (Broadbent's term). Broadbent does not specifically deal with the problem of control in his discussion of the deficiencies of this model, though the problems of stimulus-and-cause confusion, unreality of one-way processing, and strategy use all deal with this issue. As an alternative to the Y-shaped tube model that Broadbent correctly judges to be incomplete, he proposes a model based on the shape of the Maltese cross. In some ways this new model is less specific than its predecessor (is there a pipeline leading to the sensory store?), and it certainly leads one to think of different questions (attention, for example, is no longer directed to "attention"). But there still remains the problem of the higher controller, and for this model Broadbent follows a more recently traveled path.

To account for the execution and control of behavior, different theoretical possibilities exist. One approach, presented for the purpose of example only by Broadbent, is the homunculus or busy executive who decides from moment to moment what to do with the information at hand. This approach, with its corresponding problem of infinite regress in any homunculus-driven system, was avoided by Bartlett (1932) and Lashley (1951) who argued that serial behavior could be produced by organizational processes that unitized a behavioral sequence. For organized behavior, a sequence of decisions was no longer necessary. Similarly, Neisser (1967) noted that the problem of the busy executive could be handled by recourse to the computer analogue of an executive routine. He went on to say that the problem of a separate executive would "return psychology to the soul, the will, and the homunculus; it would be equivalent to explaining behavior in terms of a 'little man in the head'" (Neisser 1967, p. 295).

Broadbent, of course, is keenly aware of this psychological problem. Instead of giving the processing system at the center of the Maltese cross the decision-making power of a human, he proposes instead that processing operations are carried out by rules held in long-term storage. "Given such rules," says Broadbent, "the processing system need possess no initiative or judgment of its own." But from where do these rules come? Are they innate ideas in the sense proposed by Descartes, Plato, or other early philosophers? Are they learned and modified through a person's experience? Neisser (1967, p. 296) noted that activities such as "searching through memory" and "turning around one's schemata" are learned and, although he presented no evidence for this belief, this is consistent with his view that processes rather than representations are what we retain. Still, lest someone ask who establishes the rules, it is necessary to account for how the rules come to be made.

Broadbent, as others before him, has now stepped where Descartes feared to tread. Through a contemporary reformulation, what was considered a problem in philosophy can now be viewed within the domain of psychology. The processing rules from long-term storage may be the key to solving the age-old problem of the relationship between mind and body.

Stage models of mental processing and the additive-factor method

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The application of stage models to mental processes is attacked by Broadbent in the first part of the target article. He claims (1) that stage models are of limited applicability in three significant respects, and (2) that the additive-factor method (AFM) sometimes used in their investigation is "unsound." Difficulties and uncertainty afflict all attempts to explain observations in terms of underlying mechanisms, and any single method is of course limited, but Broadbent's particular claims result from misconceptions of both models and method.

Not all stage models are pipelines. Broadbent's "pipelines" constrain the relation between process and representation: Later processes must operate on representations that have been processed more highly – that are "further from the input." Stage models need not be constrained in this way; in general they merely partition processing operations into temporally successive components. In recently proposed stage models the second of two successive processing stages (S_2) has been related to the first (S_1) in at least three ways.

1. Completion controlled. S_2 is constrained by S_1 only insofar as S_1 must be completed before S_2 can begin, possibly because of capacity limitations in a central processor. Examples: (a) S_1 and S_2 process the first and second of two rapidly successive stimuli (Ollman 1968; Welford 1980). (b) S_1 and S_2 are successive comparisons in an exhaustive search (S. Sternberg 1969b). (c) S_2 is the reading of the second premise of a syllogism (R. J. Sternberg 1980). (d) In rapid action sequences S_1 executes the subprogram for one action unit and S_2 retrieves the subprogram for the next (S. Sternberg, Monsell, Knoll & Wright 1978).

2. Outcome contingent. What S_2 does depends on the results ("output") of S_1, but S_2 does not process that output. Examples: (a) In a self-terminating search S_2 is a further comparison process only if S_1 produces a mismatch (S. Sternberg 1969b). (b) In a visual search S_2 reallocates attention only if S_1 fails to detect (Shaw 1978). (c) A first stimulus, processed by S_1, provides a rule, or "set" according to which S_2 processes a second stimulus (Bernstein & Segal 1968).

3. Data dependent. S_2 further processes data contained in the output of S_1. Examples: (a) S_2 executes the action-unit subprogram retrieved by S_1 (S. Sternberg et al. 1978). (b) In numeral naming a translation and response-organization stage S_2 maps the numeral representation provided by an encoding stage S_1 onto a response (S. Sternberg 1969a). Of the three types of S_2–S_1 relation, only the last corresponds to Broadbent's "pipelines": S_2 follows S_1 and also operates on more highly processed information than does S_1.

Additive-factor method as inductive inference. What kind of logic is "'additive factor logic'"? Broadbent's use of this term, his claim that the AFM is "unsound logically," and his remarks about the "necessity" of certain inferences suggest that he may be confused about this matter. In this section I show how the AFM exploits the usual relations that obtain between theory and observation, and indicate which inferences are logically necessary and which are not.

Consider a theory H, the conjunction of propositions P1 and P2 about a pair of mental processes. P1 (*stages*): Processes *a* and *b* operate in distinct stages, that is, one beings only when the other is complete. (The alternative, $\overline{P1}$, is that *a* and *b* are incorporated in the same stage. For simplicity I define "stage" so that there is at least one between stimulus and response, which occupies the entire stimulus-response interval.) P2 (*selective influence*): Factors F and G influence processes *a* and *b* selectively, such that F influences the duration of *a* but not *b*, whereas G influences the duration of *b* but not *a*. (The alternative, $\overline{P2}$, is that F and G influence at least one process in common.) Weak (lacking in detail) as it is, H has a powerful implication: The mean effects of F and G on the time T_{ab} to accomplish processes *a* and *b* will be (strictly) additive (property A). Thus a change from level F_1 to level F_2 of factor F will increase T_{ab} by the same amount, regardless of the level of G, and vice versa. (The implication depends on our ability to write $T_{ab} = T_a + T_b$, when T_{ab} is measured in physical time and where T_a and T_b are the unobserved mean durations of processes *a* and *b*.) Contrary to Broadbent's claim, the implication from theory H to property A is one of logical necessity, just as in the case of implications derived from many theories.

Because theory H implies property A, falsity of A (denoted $\overline{A}$ and inferred from observation of interacting effects of F and G on T_{ab}) logically implies falsity of H (by *modus tollens*). This in turn implies that P1 is false (and processes *a* and *b* are incorporated in the same stage), or P2 is false (and factors F and G influence at least one process in common), or both are false. Whichever of the three alternatives obtains, falsity of A permits us to assert that factors F and G influence at least one stage in common and that this stage is not decomposable into (sub)stages influenced selectively by F and G; I shall use $\overline{H}$ to denote this state of affairs.

If observations confirm an implication of a theory, our degree of belief in the theory is increased, but these observations do not logically *entail* the truth of the theory. Roughly speaking, the fewer alternative plausible theories that have the same implication, the greater the increment in our belief strength. Observation of property A is thus more potent for confirming theory H insofar as there are few plausible mechanisms for which the conjunction of A and $\overline{H}$ obtains, that is, in which two factors that influence the same nondecomposable stage have additive effects. This is why Broadbent is at pains to demonstrate such mechanisms, and why the failure of both of his alleged demonstrations will be illuminating (see below).

Additional support for the implausibility of the conjunction of A and $\overline{H}$ can be derived from the following argument. Consider the one-dimensional interaction constrast from a simple 2×2 experiment (two factors, each at two levels). This contrast can take on an infinite number of possible values – a continuum from negative to positive. An additive pattern (interaction contrast zero) corresponds to only a single point on this continuum; all other patterns are interactive. The argument can readily be generalized to more complex experiments and must, of course, be elaborated to accommodate fallible data.

Just as the implausibility of the conjunction of A and $\overline{H}$ causes observation of A to give support to H, so it causes a belief in $\overline{H}$ to lead us to expect A; Broadbent is correct when he asserts that this latter relation is not one of logical necessity. Instead, both relations are governed by the normal practices of inductive inference.

Because of the relations of implications and confirmation described above, and their elaborations (S. Sternberg 1969a), patterns of factor effects, especially additive effects, have attracted considerable interest during the past decade. Factorial experiments with reaction-time measures have been seen as especially useful for inventing and selecting among relatively weak (nondetailed) theories about mental processes. Given its rejection, the weakness of a theory is an asset, because a weak theory corresponds to a large class of strong theories. (See Broadbent 1958, chap. 12.) Given confirmation, a weak theory provides only a starting point, of course, which may nonetheless significantly guide and constrain further research.

Analysis of processes out of sink. Broadbent's example of processing stages in the scullery provides several useful insights about applications of the AFM. He starts by postulating three stages in dishwashing together with factors that influence those stages selectively. Stage *a:* Turn on water. (Factor: Distance D from person to faucet.) Stage *b:* Fill sink. (Factors: Length L and breadth B of sink.) Stage *c:* Wash dishes. (Factors: Number N of dishes and their mean dirtiness DT.) The measure is the total duration T of the three stages. Consistent with the argument on which the AFM is based, the members within each of the two pairs of factors that influence the same stage, (L, B) and (N, DT), interact. The other eight two-way interactions are all zero (as are the 16 higher-way interactions; see S. Sternberg 1969a, sec. 3.4).

Broadbent next introduces two additional factors, the starting and full water levels S and F, and notes that they both influence the same (ostensibly nondecomposable) stage (sink filling, *b*) and yet have additive effects, an apparent instance of the conjunction (of $\overline{H}$ and A) on whose implausibility the AFM depends. The instance is only apparent, however; according to the AFM we should be able to decompose stage *b* into at least two (sub)stages, one influenced by S and the other by F, and indeed we can. (Sink filling is analogous to the serial-comparison stage in "memory search" that can be decomposed into the [sub]stages – individual comparisons – of which it consists; S. Sternberg 1969a.) We need only let stage b_1 correspond to filling the sink from S to some fixed intermediate level, and let stage b_2 correspond to filling it from this level to F. (If filling a sink from S to F is described as a single "process," then this argument exemplifies the decomposition of one process into more than one processing stage.)

Because stages b_1 and b_2 are *both* influenced by L and B the introduction of factors S and F creates a pattern of factor effects in which each of two additive factors (S and F) interacts with the same other factors (L and B). Broadbent's mistaken claim that the AFM associates this pattern with an "inconsistent" assignment of factors to stages is discussed below.

One experiment that would permit us further to test the existence of two separate stages b_1 and b_2 would be to find other factors that influence them selectively. Suppose that sink length L changes abruptly at the intermediate level, so that lengths in starting and final sections of the sink are L_s and L_f, respectively. Then we expect that not only will L_s and L_f have additive effects on T, but that members of the pairs (L_s, F) and (L_f, S) will, also, whereas members of the pairs (L_s, S) and (L_f, F) will interact, as will all pairs composed of one of these factors and B.

In a further elaboration, Broadbent introduces faucet stiffness, FS, which influences the time taken to open the valve. He observes that again two factors (FS and D) influence the same stage (turning on water) and yet have additive effects. Again the AFM suggests that we should be able to decompose this stage into at least two (sub)stages, each influenced by just one of the factors, and again we can: Until the person has walked to the sink (stage a_1, influenced by D but not FS) he cannot open the valve (stage a_2, influenced by FS but not D).

Starting with the supposition that scullery operation is a three-stage process, Broadbent has "observed" a pattern of factor effects. Application of the AFM to these effects and to the effects of manipulating additional factors in new "experiments" provides new insights, in the form of a more refined, five-stage theory, together with an experimental test.

Broadbent is correct when he asserts that factors that influence the same stage are not *required* to interact; the strength of the inference from additivity depends on the difficulty – experienced by Broadbent and others – of imagining plausible nondecomposable one-stage mechanisms where factor effects add. (Indeed, to encourage the imagining of such mechanisms, either physical or psychological, with precisely additive effects on mean stage duration, I will award an appropriately inscribed model stage for the best example received during the next six months.)

In a final elaboration, Broadbent supposes that FS influences the flow rate, determined by how far the valve is opened, as well as the time to open it. It follows that FS will influence stages b_1 and b_2, and will interact with all the other factors (L_s, L_f, B, S, and F) influencing those stages. In a straightforward application of the AFM to this pattern, FS (and the valve-opening process that it influences) would be associated with stages b_1 and b_2; no process influenced by FS alone (a_2) would be described as a separate stage. (This is one of the limitations of the AFM discussed in S. Sternberg 1969a, sec. 3.4.) Despite his claim, then, Broadbent has not generated a case in which factors inferred to influence different *stages* nonetheless interact. Given an appropriate definition of "process," however, he has constructed an instance in which more than one is associated by the AFM with a single processing stage.

In a more subtle analysis of factor effects one would consider the form of the interaction between FS and each of the other factors that influence sink filling, and notice that it was a *linear interaction*. Furthermore, when plotted as a function of any one of these other factors, T would be linear, with a slope dependent on FS. If the zero intercepts of such functions increased with FS, this would identify a_2 as a separate process influenced by FS (not necessarily a separate stage, however, depending on the definition of "stage"). One interpretation of the effects of FS on b_1 and b_2 would then treat them as *indirect* effects, resulting from its *direct* effect on a_2. (See S. Sternberg 1969b, note 10, for an analogous argument from a linear interaction.) It is easy to generalize this argument from the linearity of an interaction to search processes with unequal mean comparison times, sinks with irregular cross-sections, or other hydraulic domains such as reservoirs (Broadbent 1982, p. 274).

Inconsistent inferences from the additive-factor method? Can *any* pattern of factor effects be converted by the AFM into an appropriate assignment of factors to an appropriate set of one or more stages? The answer is no, and Broadbent is correct in suggesting that empirical results are conceivable from which the AFM would provide inconsistent inferences. He is wrong, however, in his identification of the offending pattern.

The inconsistency would arise from a zero low-order interaction involving two (or more) factors (leading to postulation of separate stages) together with a nonzero higher-order interaction involving the same factors with one or more others (leading to postulation of a common stage; see S. Sternberg 1969a, sec. 3.4). To retain a stage model for such a situation, we would have to assume that two (or more) factors influencing the same stage did not interact – in other words, an instance of the conjunction of A and $\bar{H}$.

The pattern that troubles Broadbent is one in which two additive factors (such as word frequency and stimulus quality in a lexical-decision task) both interact with a third factor (such as context); he claims that such a pattern leads to "inconsistency" in the assignment of factors to stages. I have already discussed such a pattern in the scullery, where S and F are additive while both interact with L (and also with B). The AFM interpretation is straightforward: The third factor influences both of the two stages that are influenced selectively by the two additive factors. The significance of exactly this pattern in numeral naming was discussed in detail when the AFM was introduced (S. Sternberg 1969a, sec. 5). There, stimulus quality (Q) and S-R compatibility (C) were reported to be additive, whereas both of these factors interacted with number (N) of S-R alternatives. The AFM led to the postulation of two stages, *stimulus encoding*, influenced by Q and N, and *translation and response organization*, influenced by C and N. That N should influence both stages was no surprise, given earlier work (Jastrow 1890).

Cascades and other hazards. Indeed "there is no safe way" to analyze mental processes: There is always the possibility of an alternative analysis that appears to mimic properties regarded as diagnostic. Broadbent notes one such interesting instance in McClelland's (1979) processes in cascade, which can be made to approximate factor additivity, despite the absence of stages, if one ignores the nonresponse trials it predicts (Ashby 1982). Fortunately, new analyses (Ashby 1982) and ingenious experimental tests (D. L. Meyer, Yantis, Osman & Smith, in press; Miller 1982) permit discrimination between stage and cascade models, and thereby reduce the hazards. On the basis of the limited evaluation thus far, and for the tasks that have been examined, Broadbent's judgment that cascading mental processes are "likely" cannot be justified.

Three biases claimed for stage models (or modelers?) It would be interesting to know whether stage models are more or less biased than other models of mental processes in the respects that Broadbent asserts, or even to know how one might determine this. Instead I mention counterexamples for each of the three biases that, according to Broadbent, afflict stage models.

1. Passivity. Stage models have often been constructed for discrete-trial reaction-time experiments in which subjects have been *instructed* to be passive until the stimulus arrives; perhaps for this reason many such models describe no prior process. Even in such paradigms, however, temporal variations in signal expectancy (Alegria & Bertelson 1970) and preparatory motor adjustment (Sanders 1983) have been considered in terms of stage models, as have the effects of processes required by an ongoing concurrent task (Logan 1978). Stage models have also been applied to paradigms in which a critical signal occurs shortly after presentation of partial (Bernstein & Segal 1968) or full (D. L. Meyer et al., in press) advance information, or after an independent stimulus possibly requiring a response (Ollman 1968; Sternberg & Scarborough 1971; Welford 1980); in none of these applications does the model describe subjects as passive before the critical signal.

2. One-way processing. Examples of stage models in which the information used at one stage of processing is no more refined, or is possibly less refined, than information used at some earlier stage are mentioned in my discussion above of completion-controlled and outcome-contingent stages. That "perceptual-cycle" processes can be incorporated into stage models and investigated using the AFM is exemplified by the verification model of word recognition (Becker 1979; Becker & Killion 1977) to which Broadbent refers.

3. Qualitative invariance. "Strategies" are qualitatively distinct processing operations underlying performance of the same task. Counterexamples to Broadbent's claim that stage models cannot easily be used in the study of strategies include applications to sentence-picture verification (MacLeod, Hunt & Mathews 1978), syllogistic reasoning (R. J. Sternberg 1980; R. J. Sternberg & Weil 1980), sensorial versus muscular preparation (D. L. Meyer et al., in press), and memory search in different sets of subjects (S. Sternberg 1975, sec. 7.3) and in aphasics versus normals (Swinney & Taylor 1971).

It is not obvious a priori whether few or many mental processes are organized as successive processing stages. If there are any, however, the AFM continues to offer a sound approach for their discovery.

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