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PROCESS REPRESENTATIONS AND DECOMPOSITIONS OF RESPONSE TIMES

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ABSTRACT. Response times (in a very general meaning of the term, including physiological latencies and durations of theoretically assumed mental actions) can be subjected to two basic forms of analysis: (a) the representation of response times by durations of unobservable processes identified by their final outcomes and developing until they meet certain termination conditions; and (b) the decomposition of response times into component durations identified by observable external factors that influence them selectively. This chapter overviews and elaborates theoretical concepts and mathematical results related to these two analyses. It begins with a general theory of process representations for arbitrary response arrangements (i.e., the rules determining which responses may co-occur within a trial). This theory extends the Grice-representability and McGill-representability analysis proposed previously for mutually exclusive responses. Then the notion of selectively influenced but (generally) interacting processes is introduced and related to that of selectively influenced but (generally) stochastically interdependent component durations: the two notions turn out to be related in an indirect and complex way. Finally, an overview is given of the available mathematical facts related to (a) the recovery of the algebraic operation connecting the response time components that are identified by the factors selectively influencing them and by the form of stochastic relationship among them (independence or perfect positive interdependence); and (b) the choice between the independence and perfect positive interdependence of signal-dependent and signal-independent components identified by the algebraic operation connecting them.

1. INTRODUCTION

This chapter is about two basic forms of the theoretical analysis of response times: the representation of response times by abstract processes with certain termination rules, and the decomposition of response times into component durations selectively influenced by different external factors. The chapter is not meant to serve as a survey of the extensive and diverse literature that bears upon these issues. Rather it relates to and somewhat extends one particular line of research, in whose development I have participated myself. The primary focus is on the logic of theoretical constructs rather than empirical facts and generalizations. In particular, the analysis is not predicated on specific assumptions concerning the form

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Key words and phrases. Response time, selective influence, decomposition into components, decomposition rule, stochastic relationship.

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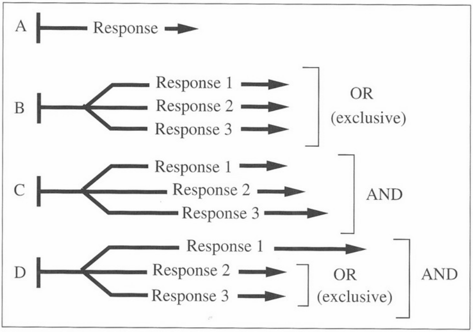

FIGURE 1. Examples of response arrangements.

of the response time distributions, except for occasionally needed constraints of a technical nature.

The term "response" refers primarily to an observable physical event, such as a key press or a certain activity level in a neuronal structure. However, to incorporate some of the traditional "information processing" issues, it is convenient to allow the term to also refer to hypothetical mental events, such as a visual representation of an object's shape or a retrieval of an item from a memory storage. In all cases the use of the term implies that responses occur within well-defined trials, that they belong to well-defined finite sets of possible responses, and that the moments when responses occur within a trial (even if theoretically derived or assumed) are viewed as (if they were) observable empirical data, subject to further analysis. In a typical experiment only one of possible responses may occur within a trial. Mutually non-exclusive responses, however, are also conceivable, such as activity bursts in several distinct neuronal structures or mental representations of different aspects of a stimulus. Figure 1 shows some of the variety of *response arrangements* to which the present discussion applies (i.e., the rules determining which responses may or may not co-occur within a trial; note that arrangements A and B correspond to the conventional simple and choice response time paradigms). Arrangements in which all responses may be withheld within a trial are also possible (e.g., a conventional disjunctive response time paradigm).

Response times, measured from some zero moment within a trial, are generally random variables. For a response arrangement like C in Figure 1, denoting the times of all possible responses by $\mathbf{T}_1, ..., \mathbf{T}_n$ (boldface letters indicate random variables), all empirical information about these response times is contained in their joint distribution function,

$$\mathcal{T}(t_1, ..., t_n; \Xi) = \text{Prob}\{\mathbf{T}_1(\Xi) \leq t_1, ..., \mathbf{T}_n(\Xi) \leq t_n\}. \quad (1)$$

Here, Ξ stands for a description of those aspects of the external situation (such as target stimulus intensity, speed-accuracy emphasis, etc.) that may vary from trial to trial, deterministically or randomly, inducing changes in the joint distribution of $\mathbf{T}_1(\Xi), ..., \mathbf{T}_n(\Xi)$. Strictly speaking, therefore, one deals here with a *family* of random vectors (and the corresponding family of distribution functions), one vector (and distribution) for every possible value of Ξ.

The joint distribution function in (1) can be made applicable to response arrangements other than C in Figure 1, with the following proviso: If a response i does not occur within a trial, then the value of $\mathbf{T}_i$ is considered indefinite (or infinitely large): in other words, $\mathbf{T}_i(\Xi) \leq t$ is then false for any t. Thus understood (1) is the universal object of response time analysis. Since response times are observable (or treated as if they were such), the joint probability distributions are (assumed to be) known, at least on a sample level.

To construct a *process representation* for a vector of response times $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$ means to theoretically derive certain n processes (neutrally referred to as *response processes*, i.e., processes preparing a response) and postulate certain *critical conditions*, so that the response i occurs if and as soon as the i-th process meets these conditions. Obviously, either the processes or the critical conditions (or both) should have stochasticity built in them to account for the randomness of response times. Figures 2 and 3 show two different process representations for a single-response arrangement (as in the simple response time paradigm). In both cases the parameters of the process change with changing values of the situation Ξ, and in both cases the critical condition is that the level of the process exceed a *preset criterion*. In Figure 2, the "McGill modeling scheme" (after McGill, 1963), the criterion is fixed whereas the process is stochastic. In Figure 3, the "Grice modeling scheme" (after Grice, 1968, 1972), the process is deterministic whereas the criterion is randomly chosen on every trial from a distribution. (Figure 3 consists of two concatenated graphs, the "response level" serving as the ordinate for the process graph and the abscissa for the criterion distribution function graph. Note that the external situation Ξ, as indicated in Figures 2 and 3, is generally a function of time within a trial.)

Contrary to tradition, *decompositions* of response times can be introduced as an issue logically unrelated to their process representations or even to response arrangements. The object of analysis here is not the joint distribution of $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$ but rather the distribution of a single random duration $\mathbf{T}(\Xi)$ derived from this joint distribution. $\mathbf{T}(\Xi)$ may be the response time for a particular response i conditioned upon its occurrence, or the time when *some* response occurs in a choice paradigm, or one of many similar constructs. Decompositions of $\mathbf{T}(\Xi)$ are contingent on the decompositions of the external situation Ξ into a list of factors, α, β, γ, ..., with crossable levels. Once these factors are listed, one can define *time components* of $\mathbf{T}(\Xi)$ as "a component $\mathbf{A}(\alpha)$, influenced exclusively by α," "a component $\mathbf{B}(\beta)$, influenced exclusively by β," etc. To decompose $\mathbf{T}(\Xi)$ means to present it as

$$\mathbf{T}(\alpha, \beta, \gamma, \dots) \stackrel{d}{=} H\{\mathbf{A}(\alpha), \mathbf{B}(\beta), \mathbf{C}(\gamma), \dots\}, \tag{2}$$

where H is some function (the *decomposition rule*), and the symbol $\stackrel{d}{=}$ stands for "is distributed as."

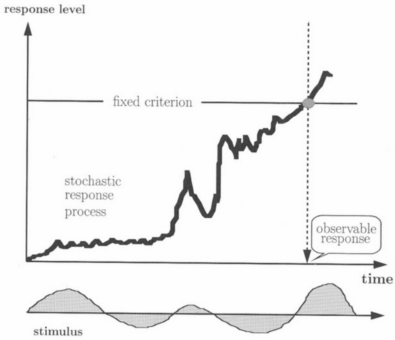

FIGURE 2. The McGill modeling scheme for a single response (explanations in text).

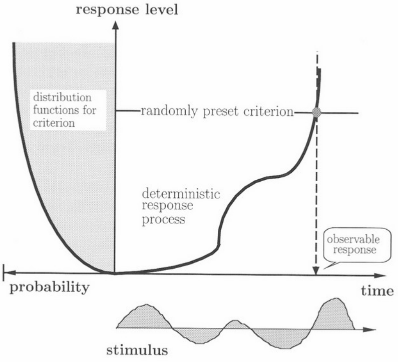

FIGURE 3. The Grice modeling scheme for a single response (explanations in text).

Note an important logical difference between process representations and decompositions of response times. Response processes are identified by their *potential effects*, the responses to which they lead if certain critical conditions are met. Any change in the external situation Ξ generally influences the course of all these processes. By contrast, time components $\mathbf{A}(\alpha)$, $\mathbf{B}(\beta)$, $\mathbf{C}(\gamma)$, etc., are identified by the changes in the external situation that *influence them selectively*: Thus $\mathbf{A}$ is *defined* as a component influenced by α, and only by α – irrespective of whether such a component exists or whether it is uniquely determinable. The time components may be interpreted as corresponding to specific (unobservable) effects, but such an interpretation is inconsequential for recovering the decomposition rule H or the distributions of the time components. The precise meaning of selective influence in its relationship with possible joint distributions of time components is a rather subtle issue, discussed later.

Another significant difference between the two issues is that on a principal level the problem of process representations lends itself to a complete solution: unless one imposes additional constraints, such as selective influence, process representations can be constructed by a universal algorithm, for any response arrangement and any family of response time vectors. By contrast, only rudimentary knowledge is available on response time decompositions; this knowledge only applies to limited choices of the decomposition rule H in Equation 2 and the simplest forms of the stochastic relationships among the time components.

2. Process representations

The problem of constructing process representations for single-response arrangements is quite simple, and the logical and operational meaning of the concepts involved is especially transparent in this case. Consider first the Grice-representation scheme (Figure 3), according to which the Ξ-dependent process $R(t;\Xi)$ representing a response time $\mathbf{T}(\Xi)$ is deterministic, and $\mathbf{T}(\Xi)$ is the time when $R(t;\Xi)$ exceeds for the first time a Ξ-independent randomly preset criterion $\mathbf{C}$. It is easy to show (Dzhafarov, 1993) that whatever the distribution function $\mathcal{T}(t;\Xi)$ for $\mathbf{T}(\Xi)$, the latter can be Grice-represented by choosing some distribution function $\mathcal{C}(c)$ for the criterion $\mathbf{C}$ and putting

$$R(t;\Xi) = \mathcal{C}^{-1}\{\mathcal{T}(t;\Xi)\}. \tag{3}$$

The choice of the criterion distribution function $\mathcal{C}(c)$ is arbitrary, except for minor technicalities.[1] Indeed, by a monotonic transformation of the "response level" axis in Figure 3 one can change $\mathcal{C}(c)$ into any other distribution function. Such a transformation, however, simultaneously changes the representing process $R(t;\Xi)$, so that its times of crossing the criterion, the only observables in the scheme, do not change. The sole role of the criterion distribution, therefore, is to calibrate the otherwise "rubber-band" axis on which both the criterion and the process assume their values. The "assumptions" that the criterion distribution has a particular form and that it is Ξ-independent are totally void of empirical content.

[1] The criterion distribution should be continuous. For technical convenience, it is preferable also to make it strictly increasing and non-negative (as in Figure 3).

The same conclusion applies to the "assumption" that the response time $\mathbf{T}(\Xi)$ can be represented by a deterministic Ξ-dependent process. It is clear from (3) that the deterministic process $R(t;\Xi)$ is just one of many possible descriptions for the distribution of $\mathbf{T}(\Xi)$, on a par with its distribution function $\mathcal{T}(t;\Xi)$, whose monotonic transformation $R(t;\Xi)$ is. In fact, with a specific choice of the criterion (namely, choosing it uniformly distributed between 0 and 1), $R(t;\Xi)$ and $\mathcal{T}(t;\Xi)$ can be made to formally coincide. At the same time, the use of the term "process" is not a misnomer here, because for any choice of the criterion the process $R(t;\Xi)$ is *physically realizable*, in the sense of causal consistency: If the external situation Ξ develops within a trial, the value of $R(t;\Xi)$ at any time t (given its initial value) only depends on the values of Ξ previous to the moment t:

$$R(t;\Xi) = R[\Xi(u)\mid_{u<t}].^2$$

Although quite elementary mathematically, the analysis above may appear surprising. It turns out that the principal idea of modeling response times by deterministic Ξ-dependent processes developing until they reach randomly present Ξ-independent criteria is not an empirically falsifiable model, but rather a theoretical language that applies to all conceivable response time distribution families. The term used in Dzhafarov (1993) is the "modeling scheme," a conceptual system that is not a model itself but that allows one to formulate all falsifiable models within its framework. Grice's (1968, 1972) original formulation of this modeling scheme was even weaker, as it allowed (unnecessarily) the criterion to depend on the external situation Ξ – and even in this weakened form the idea was widely considered too simplistic to be empirically applicable.

Any falsifiable model for response times (having been translated into the Grice scheme's language) can be of one of two kinds. It may state that the processes $R(t;\Xi)$, for one or more values of Ξ, have a particular shape when the "rubber-band" axis for their values is calibrated by the distribution of a particular form. For instance, the falsifiable part of Grice's original proposal is that the process $R(t;\Xi)$ is linear (Grice, 1968) or negative-exponential (Grice, 1972; Grice, Nullmeyer, & Spiker, 1982) when the response level axis is calibrated by a normal distribution.[3] A falsifiable model of another kind states that the processes $R(t;\Xi)$ for different values of Ξ have a particular mathematical relationship among them – without specifying the criterion distribution. For instance, in a visual motion detection model proposed in Dzhafarov and Allik (1984) and Dzhafarov, Sekuler, and Allik (1993) a moving stimulus initiates a "kinematic energy" process uniquely determined by

[2]Note that $\Xi(u)\mid_{u<t}$ is a function, that is, its values are taken with the moments at which they occur. In particular, the truncation point t is part of the function's identity, because of which t need not be included as a separate argument. A different though equivalent way of presenting the deterministic process $R(t;\Xi)$ is by a differential equation $\dot{R}(t;\Xi) = r[\Xi(u)\mid_{u\le t}, R(u;\Xi)\mid_{u\le t}]$, where the time derivative $\dot{R}(t;\Xi)$ may have to be expressed through Dirac's delta function. This representation is more readily generalizable to a vector of deterministic processes, as discussed later.

[3]An attempt to substantiate the choice of a normal distribution by such arguments as the central limit theorem is meaningless. This choice is arbitrary. At the same time, as shown in Dzhafarov (1993), the choice of a negative-exponential process on a normally calibrated axis is logically flawed.

the position-versus-time function. In such a model the question is whether one can find a single criterion distribution for all different processes.

The analysis of the McGill-representability (Figure 2) yields analogous results. According to this scheme, $\mathbf{T}(\Xi)$ is the time when a Ξ-dependent stochastic process $\mathbf{R}(t;\Xi)$ exceeds for the first time a fixed level (say, unity). Even the simplest and most restrictive versions of this scheme turn out to be mathematically equivalent to the Grice modeling scheme. They too, therefore, are merely descriptive theoretical languages. One can always McGill-represent $\mathbf{T}(\Xi)$ by computing $\mathbf{R}(t;\Xi)$ as a mathematical composition of a deterministic Ξ-dependent part $R(t;\Xi)$ and a Ξ-independent stationary noise $\mathbf{C}(t)$:

$$\mathbf{R}(t;\Xi) = G\{R(t;\Xi), \mathbf{C}(t)\}. \tag{4}$$

Except for technicalities, one is free to choose any composition function G and any stationary process $\mathbf{C}(t)$ (Ξ-independent). These two facts may appear even more surprising than the arbitrariness of the criterion distribution in the Grice modeling scheme. Nevertheless they are straightforward consequences of the equivalence between the two modeling schemes.[4] Using different composition functions (additive, multiplicative, etc.) one can construct a variety of generalizations for the stochastic processes commonly used in response time modeling (such as the diffusion processes with drift). The role of $\mathbf{C}(t)$ in (4) is precisely the same as that of the criterion in the Grice scheme: in fact, if the momentary distribution function of $G^{-1}\{1, \mathbf{C}(t)\}$ is matched with that of the criterion $\mathbf{C}$, then $R(t;\Xi)$ is the same in the two modeling schemes, in both cases computed by (3). Note that stochastic relationships among the distributions of $\mathbf{C}(t)$ at different moments of time are inconsequential: any two stochastic processes $\mathbf{R}(t;\Xi)$ with the same deterministic part $R(t;\Xi)$ and the same momentary distribution of $\mathbf{C}(t)$ represent the same response time $\mathbf{T}(\Xi)$. This shows that the McGill modeling scheme is conceptually more redundant than the Grice one.

The mathematical theory of the Grice-representability is considerably more sophisticated for multiple-response arrangements (Dzhafarov, 1993). The family of response time vectors $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$ is said to be Grice-represented by deterministic processes $R_1(t;\Xi), ..., R_n(t;\Xi)$ if there is a Ξ-independent vector of randomly preset criteria $\mathbf{C}_1$, ..., $\mathbf{C}_n$ (not necessarily stochastically independent) such that $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$ are the times when the respective processes exceed, each for the first time, their respective criteria.

The key issue here is how one understands the concept of a *vector of deterministic processes.* A single process $R(t;\Xi)$ is deterministic if its initial value is fixed and its value at time $t > 0$ only depends on the external situation Ξ (up to the moment t, if it develops in time). In the case of a vector $R_1(t;\Xi), ..., R_n(t;\Xi)$, however, one cannot just use the same definition componentwise, because the external situation Ξ here may not be the sole determinant of the processes. In addition, the

[4] G should be chosen increasing in the first argument and continuous in the second. The critical condition in the McGill scheme, $G\{R(t;\Xi), \mathbf{C}(t)\} \geq 1$, is then equivalent to $R(t;\Xi) \geq G^{-1}\{1, \mathbf{C}(t)\}$, which is the critical condition in the Grice scheme, provided the criterion distribution is matched with that of $G^{-1}\{1, \mathbf{C}(t)\}$. ($G^{-1}$ denotes the inverse of G with respect to the first argument.)

processes themselves form an "internal environment" for each other, or "interact" with each other, using the term descriptively. The definition, therefore, should be modified: processes $R_1(t;\Xi), ..., R_n(t;\Xi)$ are deterministic if their initial values are fixed and if

$$\dot{R}_i(t;\Xi) = r_i[\Xi(u)\mid_{u\leq t}, R_1(u;\Xi)\mid_{u\leq t}, ..., R_n(u;\Xi)\mid_{u\leq t}],$$

where the meaning of the time derivative $\dot{R}_i$ is the same as in Footnote 2.

Superficially the definition just given may seem unnecessarily complicated, because there may seem to be no way of changing one of the processes, say $R_1(t;\Xi)$, in order to observe the effect of this change on, say, $R_2(t;\Xi)$, while keeping the external situation Ξ unchanged. One cannot, for example, evaluate the impact of $R_1(t;\Xi)$ on other processes by either including or not including the first response in the response arrangement, because this would mean a manipulation of the external situation whose part the response arrangement is (provided it varies, as in this example, from trial to trial). This general argument, however, overlooks the mechanism of *process termination* built in the Grice modeling scheme. According to this scheme, the i-th response is generated if and when $R_i(t;\Xi)$ crosses its respective criterion, $\mathbf{C}_i$, at which moment the process is terminated. The terminated process can be thought of as not being defined or being set equal to infinity after the termination moment – whatever the formalization, we have here a change in the course of the process that is not determined by changes in the external situation. By the definition of deterministic processes, as soon as this happens (i.e., the i-th response occurs) the remaining processes generally change their course as compared to how they would have proceeded if the response did not occur.

A simple contemplation reveals that this is the only mechanism by which deterministic processes may develop differently in different trials with one and the same external situation. Because of this, the definition of deterministic processes can be made more specific: the value of $R_i(t;\Xi)$ at time $t > 0$ only depends on $i, \Xi(u)\mid_{u<t}$ and the list of response times (identified by responses) previous to the moment t. The way the occurrence of a response affects the remaining processes is different for different response arrangements. In the case when all responses are mutually exclusive (like in arrangement B in Figure 1) the occurrence of a response should "freeze" the upward development in all other processes – they must not increase beyond their achieved values till the end of the trial, in order to be prevented from crossing their criteria, however close these criteria might be to the achieved positions.

For an arrangement like C in Figure 1 the pattern of interactions among the processes may be more complex. Figure 4 provides an illustration involving three processes, $R_1(t;\Xi)$, $R_2(t;\Xi)$, and $R_3(t;\Xi)$, whose development is shown for a particular Ξ and a particular triad of preset criteria. The graphs in this figure have the same structure as Figure 3 (the axes are not labeled to avoid clutter). Small circles, vertically aligned, indicate moments when one of the processes terminates. The solid lines stemming from the origins show the development of the three processes until $R_1(t;\Xi)$ crosses its criterion; if this did not occur, the processes would have continued as shown by the dashed lines. The process $R_1(t;\Xi)$ does terminate, however, and this causes $R_2(t;\Xi)$, and $R_3(t;\Xi)$ to change their course (solid lines stemming from the first circle). The continuation after $R_2(t;\Xi)$ crosses its criterion is considered analogously.

Having established the meaning of the Grice-representability for multiple-response arrangements, it turns out that the main result here is essentially a straightforward multivariate analogue of that for single-response arrangements. Whatever the family of response time vectors $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$, it can be Grice-represented by a vector of deterministic processes $R_1(t;\Xi),\ldots,R_n(t;\Xi)$ coupled with a Ξ-independent vector of criteria $\mathbf{C}_1$, ..., $\mathbf{C}_n$. Moreover, the joint distribution function for the criteria can be chosen arbitrarily, except for some weak technical constraints that I will not discuss here. Analogous to the single-response case, the sole role of the criteria is to establish an n-dimensional system of coordinates for the vector $R_1(t;\Xi),\ldots,R_n(t;\Xi)$. For instance, choosing the criteria $\mathbf{C}_1$, ..., $\mathbf{C}_n$ stochastically independent (which is always an option) corresponds to making these coordinates orthogonal.

In Dzhafarov (1993), the Grice-representability is only proved for mutually exclusive responses (like in arrangement B in Figure 1), that is, it is established there for the situation where the only observable response time is associated with the process that reaches its criterion first. The way to generalize this result to arbitrary response arrangements is simple: it consists in successively applying the Grice-representability analysis to intervals between responses (the intercompletion times, in Townsend's terminology; Townsend, 1974) while considering the list of previously given responses and response times as part of the external situation. Let $[\mathbf{I}_{(1)}(\Xi),\mathbf{T}_{(1)}(\Xi)]$ be the identity and time of the response given first, $[\mathbf{I}_{(2)}(\Xi),\mathbf{T}_{(2)}(\Xi)],\ldots,[\mathbf{I}_{(n)}(\Xi),\mathbf{T}_{(n)}(\Xi)]$ being defined analogously. Consider the following sequence:

$$[\mathbf{I}_{(1)}(\Xi),\mathbf{T}_{(1)}(\Xi)]$$

$$\{\mathbf{I}_{(2)}(\Xi),\mathbf{T}_{(2)}(\Xi) \mid [\mathbf{I}_{(1)}(\Xi),\mathbf{T}_{(1)}(\Xi)] = (i_1,t_1)\}$$

$$\ldots$$

$$\{\mathbf{I}_{(n)}(\Xi),\mathbf{T}_{(n)}(\Xi)] \mid [\mathbf{I}_{(1)}(\Xi),\mathbf{T}_{(1)}(\Xi)] = (i_1,t_1),\ldots,[\mathbf{I}_{(n-1)}(\Xi),\mathbf{T}_{(n-1)}(\Xi)] = (i_{n-1},t_{n-1})\}.$$

The bivariate distribution of these "label and time" variables is uniquely computable from the joint distribution of $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$. Let a Ξ-independent vector of criteria $\mathbf{C}_1$, ..., $\mathbf{C}_n$ be chosen. The theory presented in Dzhafarov (1993) allows one to compute processes $R_1(t;\Xi),\ldots,R_n(t;\Xi)$ such that $[\mathbf{I}_{(1)}(\Xi),\ \mathbf{T}_{(1)}(\Xi)] = (i,t)$ if and only if the process $R_i(t;\Xi)$ crosses its criterion at time t while the other processes are still below their criteria.[5] In other words, knowing $[\mathbf{I}_{(1)}(\Xi),\mathbf{T}_{(1)}(\Xi)]$ one can reconstruct the processes up to the first circle in Figure 4.

[5]The actual computation of the processes involves differential equations that may or may not be solvable analytically. If the criteria are chosen stochastically independent, however, a closed form solution exists. The potential crossing times for these processes (i.e., the crossing times for each of the processes conditioned upon its finishing first) are then stochastically independent random variables whose distributions, save for technical details, are derived by different means in Townsend (1976) and Marley and Colonius (1992).

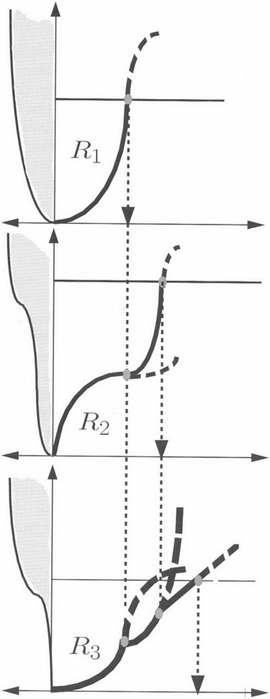

FIGURE 4. A Grice model for three non-exclusive responses (explanations in text).

Assuming now that $[\mathbf{I}_{(1)}(\Xi), \mathbf{T}_{(1)}(\Xi)] = (i_1, t_1)$, redefine the criteria as the $(n-1)$-component vector

$$\mathbf{C}_1 - R_1(t_1;\Xi), ..., \mathbf{C}_{i_1-1} - R_{i_1-1}(t_1;\Xi), \mathbf{C}_{i_1+1} - R_{i_1+1}(t_1;\Xi), ..., \mathbf{C}_n - R_n(t_1;\Xi),$$

and take as a new multidimensional origin the moment t_1 and the positions

$$R_1(t_1;\Xi), ..., R_{i_1-1}(t_1;\Xi), R_{i_1+1}(t_1;\Xi), ..., R_n(t_1;\Xi).$$

Now applying Dzhafarov's (1993) theory to the conditional "label and time" variable $\{\mathbf{I}_{(2)}(\Xi), \mathbf{T}_{(2)}(\Xi) \mid [\mathbf{I}_{(1)}(\Xi), \mathbf{T}_{(1)}(\Xi)] = (i_1, t_1)\}$, one reconstructs the continuations for the $n-1$ processes remaining after the first response, until one of them crosses its criterion (as between the first and second circles in Figure 4). The following steps are made analogously, leading from one process termination to another, until one exhausts all the processes. Obviously, a complete Grice-representation of the family of response time vectors $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$ requires that the entire procedure is replicated across all possible sequences $(i_1, t_1), ..., (i_{n-1}, t_{n-1})$ and for all possible values of Ξ.

Note that the stochastic relationship among the criteria does not determine the stochastic relationship among observable response times – in addition one has to know the pattern of interactions among the deterministic processes. For instance, if the criteria are chosen stochastically independent, the times of different responses are stochastically independent if and only if the processes representing them do not interact (i.e., if the solid and dashed lines in Figure 4 coincide).[6]

The equivalence between the Grice and McGill modeling schemes for multiple-response arrangements is established in the same way as it is for single-response arrangements. Having chosen (essentially arbitrarily) some composition functions G_1, ..., G_n, one can always McGill-represent response times $\mathbf{T}_1(\Xi)$, ..., $\mathbf{T}_n(\Xi)$ by stochastic processes $\mathbf{R}_1(t;\Xi)$, ..., $\mathbf{R}_n(t;\Xi)$ computed as

$$\mathbf{R}_i(t;\Xi) = G_i\{R_i(t;\Xi), \mathbf{C}_i(t)\}, \qquad i = 1, ..., n,$$

so that the i-th response occurs when $\mathbf{R}_i(t;\Xi)$ crosses a unity level. Here, $\mathbf{C}_1(t)$, ..., $\mathbf{C}_n(t)$ is a stationary Ξ-independent vector of noise processes that, save for technicalities, can be chosen arbitrarily. The deterministic parts $R_1(t;\Xi)$,..., $R_n(t;\Xi)$ can be made to coincide with the deterministic processes in the Grice modeling scheme if the joint distribution of $\mathbf{C}_1$, ..., $\mathbf{C}_n$ in that scheme is chosen to be identical with the momentary joint distribution of $G_1^{-1}\{1, \mathbf{C}_1(t)\}$, ..., $G_n^{-1}\{1, \mathbf{C}_n(t)\}$ (see Footnote 4).

Once again we come to the conclusion, this time with no restrictions on response arrangements, that the most principal ideas underlying the construction of process representations for response times (such ideas as "deterministic processes cross random criteria," "stochastic processes cross a fixed criterion," "criteria are stimulus-independent," "processes horse-race for their individual criteria," etc.) are not empirically testable. In a sense one could say that they are testable in conjunction with other assumptions, but even this would not be satisfactory: Indeed, one would not say, for example, that the non-falsifiable idea of representing a random variable by its distribution function is testable in conjunction with the assumption that the distribution is normal. The Grice and McGill representations, as defined in this section, form universally applicable theoretical languages allowing one to formulate within their frameworks all conceivable testable propositions. One

[6]If the criteria are chosen stochastically independent but the processes do interact, then the potential crossing times for the processes are stochastically independent random variables *if counted from the moment of the last response.* Townsend and Ashby (1983) call this "within-stage independence," and Vorberg (1990) derives the distribution of the potential crossing times using a combination of the step-by-step reconstruction just presented with the technique mentioned in Footnote 5.

may decide, of course, to formulate one's models in other, equally non-falsifiable languages (involving, e.g., processes interacting with criteria, criteria that are non-stationary stochastic processes, criteria coupled with deadlines, etc.) but such a decision cannot be construed as aimed at overcoming limitations of the Grice modeling scheme or the simplest versions of the McGill modeling scheme – because no such limitations exist.

3. Selective influence

Although most of the concepts discussed in this section are quite general, the primary focus is on a special case of (2), involving just two time components selectively influenced by two factors:

$$\mathbf{T}(\alpha,\beta) \overset{d}{=} \mathbf{A}(\alpha) \diamond \mathbf{B}(\beta). \tag{5}$$

The decomposition rule here is, for convenience, presented as an algebraic operation $\diamond$. The decomposed duration $\mathbf{T}(\alpha,\beta)$ is the only observable in this formulation; for this reason I will refer to $\mathbf{T}(\alpha,\beta)$ as the "response time," even though it is generally computed from a joint distribution of response times as explained in the introduction. A precise definition of selectively influenced time components is given below. The meaning, however, is obvious when $\mathbf{A}(\alpha)$ and $\mathbf{B}(\beta)$ are stochastically independent (for any given values of α, β).

The traditional approach consists in treating the time components $\mathbf{A}(\alpha)$ and $\mathbf{B}(\beta)$ as durations of separate processes whose developments are selectively influenced by the factors α and β. It is often assumed, based on this interpretation, that the decomposition rule in (5) can only be one of three operations: *plus* (the two processes are serially concatenated), *maximum*, or *minimum* (the two processes develop in parallel until the termination of both of them, in the case of *maximum*, or either one of them, in the case of *minimum*).[7] To understand the merits of this approach, one has to begin with clarifying the notion of *processes selectively influenced by different factors*. Using, for simplicity, the language of the Grice modeling scheme, the most general definition involving two such processes would be

$$\begin{aligned} \dot{R}_1(t;\alpha,\beta) &= r_1[\alpha, R_1(u;\alpha,\beta)\mid_{u\le t}, R_2(u;\alpha,\beta)\mid_{u\le t}],\\ \dot{R}_2(t;\alpha,\beta) &= r_2[\beta, R_1(u;\alpha,\beta)\mid_{u\le t}, R_2(u;\alpha,\beta)\mid_{u\le t}], \end{aligned} \tag{6}$$

where I write α and β instead of more rigorous $\alpha(u)\mid_{u\le t}$ and $\beta(u)\mid_{u\le t}$. For the present purposes it is sufficient to only consider two special cases of this definition.

In the most restrictive case,

$$\begin{aligned} R_1(t;\alpha,\beta) &= R_1[t;\alpha, I_2(t)],\\ R_2(t;\alpha,\beta) &= R_2[t;\beta, I_1(t)], \end{aligned}$$

where $I_i(t)$ is an indicator variable whose value is, say, 0 or 1 depending on whether or not the i-th process has terminated by the moment t. A pair of such processes is shown in Figure 5, whose structure is essentially the same as that of Figure 4. Suppose that the two processes are linear on axes calibrated by some choice of the criteria $\mathbf{C}_1$, $\mathbf{C}_2$ (for now they may be thought to be stochastically independent). R_1

[7]In the case of *minimum* the longer of the two durations is, of course, only "potential," the duration the process would have had had it finished first.

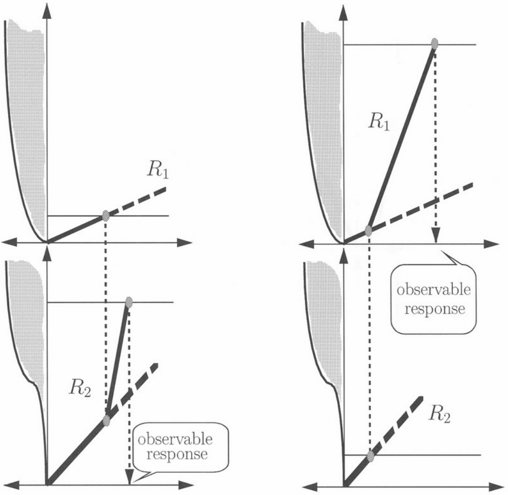

FIGURE 5. Deterministic selectively influenced parallel processes (explanations in text).

develops with the rate v_α (that only depends on α) if R_2 is still in progress, but as soon as R_2 terminates (right panel) R_1 increments its rate to hv_α; if R_1 terminates first (left panel), then R_2 whose rate before that was v_β (only depending on β) increments it to hv_β. The observable response time $\mathbf{T}(\alpha,\beta)$ is the time when all processing ends, that is, $\mathbf{T}(\alpha,\beta)$ is the maximum of two durations: of the process R_1 and of the process R_2 (a "parallel-AND" connection, in traditional terms).

The second special case of the definition of selectively influenced interacting processes, (6), is slightly less restrictive:

$$R_1(t;\alpha,\beta) = R_1[t;\alpha, J_2(t)],$$
$$R_2(t;\alpha,\beta) = R_2[t;\beta, J_1(t)],$$

where $J_i(t)$ equals the termination time for the i-th process if it has terminated by the moment t, and $J_i(t)$ is undefined (or equal to infinity) otherwise. A pair of such processes is shown in Figure 6 (a "fixed-order serial" connection). Here, the process R_1, while in progress, completely "inhibits" the process R_2 (i.e., keeps it below the minimum level of its criterion); after R_1 has terminated, R_2 begins developing and

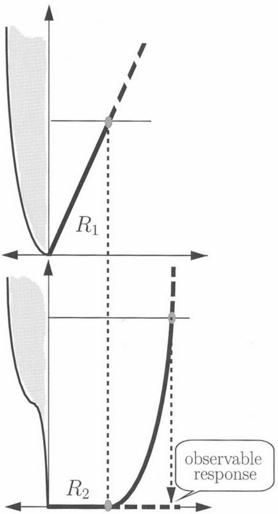

FIGURE 6. Deterministic selectively influenced fixed-order serial processes (explanations in text).

the moment at which it reaches its criterion coincides with the observable response time $\mathbf{T}(\alpha,\beta)$. Suppose that with some choice of the criteria $\mathbf{C}_1$, $\mathbf{C}_2$ (again, for now they may be considered stochastically independent), R_1 develops linearly with the rate v_α (that only depends on α); after it terminates, R_2 develops as

$$R_2[t;\beta,J_1(t)] = v_\beta\left[t^p - J_1(t)^p\right]^{1/p}, p \geq 1.$$

It is easy to derive that for the parallel-AND connection in Figure 5,

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} \min\{\mathbf{C}_1/v_\alpha, \mathbf{C}_2/v_\beta\}(1-h^{-1}) + \max\{\mathbf{C}_1/v_\alpha, \mathbf{C}_2/v_\beta\}h^{-1},$$

whereas for the serial connection in Figure 6,

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} \left[(\mathbf{C}_1/v_\alpha)^p + (\mathbf{C}_2/v_\beta)^p\right]^{1/p}.$$

Varying the values of h or p, one can relate the results to decomposition formula (5) by renaming the terms depending only on v_α and $\mathbf{C}_1$ into $\mathbf{A}(\alpha)$ and the terms depending only on v_β and $\mathbf{C}_2$ into $\mathbf{B}(\beta)$. One can observe then that the parallel-AND and fixed-order serial connections shown in Figures 5 and 6 yield a wide variety of different decomposition rules $\diamond$, including the familiar

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} max\{\mathbf{C}_1/v_\alpha, \mathbf{C}_2/v_\beta\} = max\{\mathbf{A}(\alpha), \mathbf{B}(\beta)\}, \qquad \text{when } h = 1,$$

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} \{\mathbf{C}_1/2v_\alpha + \mathbf{C}_2/2v_\beta\} = \mathbf{A}(\alpha) + \mathbf{B}(\beta), \qquad \text{when } h = 2,$$

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} min\{\mathbf{C}_1/v_\alpha, \mathbf{C}_2/v_\beta\} = min\{\mathbf{A}(\alpha), \mathbf{B}(\beta)\}, \qquad \text{when } h = \infty,$$

for the parallel-AND connection, and

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} \{\mathbf{C}_1/v_\alpha + \mathbf{C}_2/v_\beta\} = \mathbf{A}(\alpha) + \mathbf{B}(\beta), \qquad \text{when } p = 1,$$

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} max\{\mathbf{C}_1/v_\alpha, \mathbf{C}_2/v_\beta\} = max\{\mathbf{A}(\alpha), \mathbf{B}(\beta)\}, \qquad \text{when } p = \infty,$$

for the serial connection.

These simple examples demonstrate several things. First, they show that the operations *plus*, *minimum*, and *maximum* in the domain of time components need not correspond to, respectively, serial, parallel-OR, and parallel-AND arrangements in the domain of hypothetical processes, *even if the selective influence by the factors α and β holds both for the time components and for the processes.* Second, by setting h and p equal to values different from those above, one can see that the *plus*, *minimum*, and *maximum* do not have a privileged status among a variety of possible decomposition rules. Such decomposition rules as, say, the "Minkowski-norm" operations $[\mathbf{A}(\alpha)^p + \mathbf{A}(\beta)^p]^{1/p}$ are as realizable physically at the unconventional values of $p = 2$ or 3 as they are for the conventional $p = 1$ or ∞. Third, the examples show that the time components in (5) can *characterize* certain processes *without being their durations*: for instance, neither of the two additive time components in the case $h = 2$ of the parallel-AND connection is the duration of either of the two processes. Finally, the examples show that selectively influenced (interacting) processes need not have selectively influenced durations. It is easy to check that the durations $\mathbf{T}_1(\alpha,\beta)$ and $\mathbf{T}_2(\alpha,\beta)$ of (the non-zero portions of) R_1 and R_2 are not selectively influenced by α and β, because of which it is not surprising that, say, for $h = 2$ in the parallel-AND connection

$$\max\{\mathbf{T}_1(\alpha,\beta), \mathbf{T}_2(\alpha,\beta)\} \stackrel{d}{=} \mathbf{A}(\alpha) + \mathbf{B}(\beta),$$

or that for $p = \infty$ in the serial connection

$$\mathbf{T}_1(\alpha,\beta) + \mathbf{T}_2(\alpha,\beta) \stackrel{d}{=} \max\{\mathbf{A}(\alpha), \mathbf{B}(\beta)\}.$$

Having established that the relationship between selectively influenced processes and selectively influenced time components is both indirect and complex, it seems reasonable to dissociate these two issues. The approach suggested in Dzhafarov and Schweickert (1995) consists in treating decomposition (5) as a structural property of the observable response time, $\mathbf{T}(\alpha,\beta)$, rather than evidence for a particular processing architecture. A time component, say $\mathbf{A}(\alpha)$, of $\mathbf{T}(\alpha,\beta)$ can be viewed as a "would-be" version of $\mathbf{T}(\alpha,\beta)$: The response time that would be observed if it were only affected by one factor (in this case, α). The problem of decomposing $\mathbf{T}(\alpha,\beta)$ according to (5) becomes, therefore, the one of determining the algebraic operation by which the factual response time $\mathbf{T}(\alpha,\beta)$ can be computed from its two "would-be" forms. The first step in dealing with this problem is to define the very notion of the time components being selectively influenced by different factors; so far, I only used this notion for the case of stochastically independent components. The account below is a systematic version of those given in Dzhafarov (1992) and Dzhafarov and Schweickert (1995).

Any two random variables (A, B) whose joint distribution depends on some set of variables Ξ can be presented as

$$(\mathbf{A},\mathbf{B}) = \{A(\Xi, \mathbf{P}_1, \mathbf{P}_2), B(\Xi, \mathbf{P}_1, \mathbf{P}_2)\},$$

where $\mathbf{P}_1$,$\mathbf{P}_2$ are stochastically independent random variables uniformly distributed between 0 and 1, and A, B are some functions.[8] (This simple mathematical fact has interesting philosophical implications: *all stochasticity in the dependence of some random variables on external factors can be relegated to random variables that do not depend on these factors.*)

When Ξ is (α, β), it is natural to adopt the following definition: **A** and **B** are selectively influenced by factors α and β, respectively, if (and only if) they can be presented as

$$(\mathbf{A},\mathbf{B}) = \{A(\alpha, \mathbf{P}_1, \mathbf{P}_2), B(\beta, \mathbf{P}_1, \mathbf{P}_2)\}. \tag{7}$$

A special case of this representation is obtained when the function A depends on $\mathbf{P}_1$, $\mathbf{P}_2$ only through some transformation $\mathbf{C}_1 = C_1(\mathbf{P}_1,\mathbf{P}_2)$, and the function B only through some transformation $\mathbf{C}_2 = C_2(\mathbf{P}_1,\mathbf{P}_2)$:

$$(\mathbf{A},\mathbf{B}) = \{A^\star(\alpha, \mathbf{C}_1), B^\star(\beta, \mathbf{C}_2)\}, \tag{8}$$

where the joint distribution of $\mathbf{C}_1$,$\mathbf{C}_2$ does not depend on either α or β. Thus in all examples discussed earlier in connection with Figures 5 and 6 one can drop the requirement that $\mathbf{C}_1$ and $\mathbf{C}_2$ (the criteria) be stochastically independent: The components $\mathbf{C}_1/v_\alpha$ and $\mathbf{C}_2/v_\beta$, for instance, are selectively influenced by α and β irrespective of the joint distribution of $\mathbf{C}_1$ and $\mathbf{C}_2$. The essence of this definition is that the selectivity in the time components' dependence on external factors and the components' stochastic interdependence are logically orthogonal.

It is useful to relate this definition to two other concepts proposed in the literature with the intent of capturing the same relationship. The first is the *marginal selectivity* (Townsend & Schweickert, 1989), a weak requirement that the marginal distributions of the components **A** and **B** in (5) only depend on α and β, respectively. This is obviously implied by the above definition of selective influence. The second notion is that of *indirect nonselective influence* (Townsend, 1984; Townsend & Ashby, 1983; Townsend & Thomas, 1994) which takes place when **A** and **B** are stochastically interdependent but either the conditional distribution of $\mathbf{A}|\mathbf{B}$ only depends on α or the conditional distribution of $\mathbf{B}|\mathbf{A}$ only depends on β. The example associated with Figure 6 provides an illustration: If the criteria $\mathbf{C}_1$

[8] This proposition is a multivariate version of Smirnov's fundamental representation used in Monte-Carlo simulations (e.g., Yermalov, 1971). Let, for example, B be the inverse of the marginal distribution function for **B** (depending on Ξ). Then $\mathbf{B} = B(\Xi, \mathbf{P}_2)$. Let $\mathcal{Q}$ be the inverse of the conditional distribution function for **A** given a value of **B** (also depending on Ξ). Then $\mathbf{A} = \mathcal{Q}[\Xi, \mathbf{P}_1 \mid B(\Xi, \mathbf{P}_2)]$, which can be written as $A(\Xi, \mathbf{P}_1, \mathbf{P}_2)$. In the text I use a symmetrical version of this representation. Observe that by this construction A and B can always be made increasing in, respectively, $\mathbf{P}_1$ and $\mathbf{P}_2$. The generalization to more than two components is trivial.

and $\mathbf{C}_2$ are stochastically independent, then the duration of the second process, $[(\mathbf{C}_1/v_\alpha)^p + (\mathbf{C}_2/v_\beta)^p]^{1/p}$, does not depend on α other than through the duration of the first process, $\mathbf{C}_1/v_\alpha$. (This is not true, however, for interdependent $\mathbf{C}_1$ and $\mathbf{C}_2$.) It is easy to see that the indirect nonselective influence and the selective influence in the sense of (7) or (8) are mutually exclusive concepts. The components $\mathbf{C}_1/v_\alpha$ and $\mathbf{C}_2/v_\beta$, to use this example again, are selectively influenced by α and β but for interdependent $\mathbf{C}_1$ and $\mathbf{C}_2$ the conditional distribution of $\mathbf{C}_1/v_\alpha$ given $\mathbf{C}_2/v_\beta = const$ will depend on both α and β. The indirect nonselective influence, therefore, must not be treated as a generalization or even analogue of selective influence.

4. Decompositions

For any given decomposition rule $\diamond$, decomposition (5) is not well-defined unless one specifies the stochastic relationship between the selectively influenced response time components $\mathbf{A}(\alpha) = A(\alpha,\mathbf{P}_1,\mathbf{P}_2)$ and $\mathbf{B}(\beta) = B(\beta,\mathbf{P}_1,\mathbf{P}_2)$, as defined in (7). This stochastic relationship is determined by the functions A and B since the joint distribution of $\mathbf{P}_1$, $\mathbf{P}_2$ is fixed. A general formulation of the decomposition problem, therefore, is as follows: given (a family of) observable response times $\mathbf{T}(\alpha,\beta)$, determine all $(A, B, \diamond)$ such that decomposition (5) holds. There is no known way of solving this problem without either severely restricting the class of possible response time distributions (which is not an option as the present work only deals with distribution-free considerations), or severely restricting the class of possible triads $(A, B, \diamond)$. The following is an account of results established for two special versions of the decomposition problem. In one of them, the decomposition rule $\diamond$ is being sought within a wide class of operations under the assumption that the functions A and B induce a known (and very simple) stochastic relationship between $\mathbf{A}(\alpha)$ and $\mathbf{B}(\beta)$. In another, the choice is being made between two such simple forms of stochastic relationship under the assumption[9] that the decomposition rule is known.

The two simple forms of stochastic relationship just mentioned are (*stochastic*) *independence* and *perfect positive* (*stochastic*) *interdependence*, formally obtained as special cases of representation (8). If $\mathbf{C}_1$ and $\mathbf{C}_2$, that can be referred to as the "sources of random variability," are stochastically independent (in symbols, $\mathbf{C}_1 \perp \mathbf{C}_2$), then so are the time components, $\mathbf{A}(\alpha) \perp \mathbf{B}(\beta)$. If $\mathbf{C}_1 = \mathbf{C}_2$ (i.e., the time components have a common source of random variability) and if the functions $A^\star$ and $B^\star$ are increasing transformations of each other (for any given α, β), then we have the case of perfect positive interdependence, in symbols, $\mathbf{A}(\alpha) \| \mathbf{B}(\beta)$. In this case the time components vary randomly but always "increase and decrease together."

The theory presented in Dzhafarov and Schweickert (1995) is aimed at the recovery of the decomposition rules for which

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} \mathbf{A}(\alpha) \diamond \mathbf{B}(\beta), \mathbf{A}(\alpha) \stackrel{s}{—} \mathbf{B}(\beta), \tag{9}$$

[9]Here and in the previous sentence, the "assumptions" should be understood as part of the definition of the components for which one wishes to determine the unknown connecting operation or unknown stochastic relationship.

where $\overset{s}{-}$ stands either for $\perp$ (decomposition into independent components) or for $\|$ (decomposition into perfectly positively interdependent components). The theory requires that the distribution of $\mathbf{T}(\alpha,\beta)$ be known at the four treatments of a 2×2 factorial design, $(\alpha_1,\alpha_2)\times(\beta_1,\beta_2)$, and that both factor manipulations be *effective*. Denoting $\mathbf{T}_{ij} = \mathbf{T}(\alpha_i,\beta_j)$, $i = 1,2, j = l,2$, the effectiveness means that the unordered pair of the random variables $(\mathbf{T}_{11},\mathbf{T}_{22})$ differs from the pair $(\mathbf{T}_{12},\mathbf{T}_{21})$.[10]

The following proposition is referred to as the $(\diamond)$-test under the stochastic relationship $\overset{s}{-}$:

$$\mathbf{T}_{11} \diamond \mathbf{T}_{22} \overset{d}{=} \mathbf{T}_{12} \diamond \mathbf{T}_{21} \ (\mathbf{T}_{11} \overset{s}{-} \mathbf{T}_{22}, \mathbf{T}_{12} \overset{s}{-} \mathbf{T}_{21}). \tag{10}$$

If this proposition holds, then the $(\diamond)$-test is called *successful* under the stochastic relationship $\overset{s}{-}$.

It is convenient to explain the meaning of (10) on a sample level, as this simultaneously provides a lead to a statistical realization of the decomposition tests (Cortese & Dzhafarov, 1996; Dzhafarov & Cortese, 1996). Let $\{\mathbf{T}_{ij}^1, ..., \mathbf{T}_{ij}^n\}$ be a random sample from $\mathbf{T}_{ij}$ ($i = 1,2, j = 1,2$). Pairing the sampled values for $\mathbf{T}_{11}$ with those for $\mathbf{T}_{22}$ (in no particular order) and doing the same with $\mathbf{T}_{12}$ and $\mathbf{T}_{21}$, one forms two sequences,

$$\{\mathbf{T}_{11}^1 \diamond \mathbf{T}_{22}^1, ..., \mathbf{T}_{11}^n \diamond \mathbf{T}_{22}^n\} \text{ and } \{\mathbf{T}_{12}^1 \diamond \mathbf{T}_{21}^1, ..., \mathbf{T}_{12}^n \diamond \mathbf{T}_{21}^n\}. \tag{11}$$

The $(\diamond)$-test is successful under independence, if and only if the empirical distribution functions based on these two sequences converge to one and the same population distribution function as $n \to \infty$. The limit distribution is, obviously, that of $\mathbf{T}_{11}\diamond\mathbf{T}_{22}$ $(\mathbf{T}_{11}\perp\mathbf{T}_{22})$ and $\mathbf{T}_{12}\diamond\mathbf{T}_{21}$ $(\mathbf{T}_{12}\perp\mathbf{T}_{21})$. For perfect positive interdependence the sample-level account is essentially the same, except that the samples have to be ordered first, $\{\mathbf{T}_{ij}^{(1)} \leq ... \leq \mathbf{T}_{ij}^{(n)}\}$, and the paired values should have identical quantile ranks. The $(\diamond)$-test is successful under perfect positive interdependence if and only if the empirical distribution functions based on thus formed sequences

$$\{\mathbf{T}_{11}^{(1)} \diamond \mathbf{T}_{22}^{(1)} \leq ... \leq \mathbf{T}_{11}^{(n)} \diamond \mathbf{T}_{22}^{(n)}\} \text{ and } \{\mathbf{T}_{12}^{(1)} \diamond \mathbf{T}_{21}^{(1)} \leq ... \leq \mathbf{T}_{12}^{(n)} \diamond \mathbf{T}_{21}^{(n)}\} \tag{12}$$

converge to one and the same population distribution function as $n \to \infty$. The limit distribution here is that of $\mathbf{T}_{11}\diamond\mathbf{T}_{22}$ $(\mathbf{T}_{11}\|\mathbf{T}_{22})$ and $\mathbf{T}_{12}\diamond\mathbf{T}_{21}$ $(\mathbf{T}_{12}\|\mathbf{T}_{21})$.

Assume now that $a \diamond b$ is an associative and commutative operation, such as $min\{a,b\}, max\{a,b\}, a+b, a\times b, (a^k+b^k)^{1/k}$, etc. It is easy to establish that if $\mathbf{T}(\alpha,\beta)$ is $(\diamond)$-decomposable under a stochastic relationship $\overset{s}{-}$, then for any 2×2 design the $(\diamond)$-test is successful under the same $\overset{s}{-}$. For the case when $\diamond$ is addition and $\overset{s}{-}$ is $\perp$ (additive decomposition into independent components) this statement has been long since known (Ashby & Townsend, 1980; Roberts & Sternberg, 1992), but even for *maximum* and *minimum*, the "classical" alternatives to addition, the precise analogy has been overlooked.

[10]In fact the requirement is stronger: one of the identities $max\{F_{12}(t), F_{21}(t)\} \equiv max\{F_{11}(t), F_{22}(t)\}$ and $min\{F_{12}(t), F_{21}(t)\} \equiv min\{F_{11}(t), F_{22}(t)\}$ must not be satisfied (F_{ij} being the distribution function for $\mathbf{T}_{ij}$). For all practical purposes, however, all one has to be concerned with is the effectiveness of the factor manipulations.

The just formulated necessary condition for ($\diamond$)-decomposability can, in fact, be generalized beyond the associative and commutative operations. Let us call an operation $\star$ *renderable* by an operation $\diamond$ if for some functions f and g, both increasing or both decreasing,

$$a \star b \equiv f(a) \diamond g(b).$$

For example, the non-associative and non-commutative operations $pa + qb$ and $a^p + b^q$, where p and q are constants of the same sign, are both renderable by addition. It is easy to verify now that the following generalization holds: If $\mathbf{T}(\alpha,\beta)$ is ($\star$)-decomposable under a stochastic relationship $\overset{s}{-}$, and if $\star$ is renderable by an associative and commutative operation $\diamond$, then for any 2×2 design the ($\diamond$)-test is successful under the same $\overset{s}{-}$. The verification is based on observing that $f[\mathbf{A}(\alpha)]$ and $g[\mathbf{B}(\beta)]$) are selectively influenced by α and β under the same stochastic relationship ($\perp$ or $||$) as $\mathbf{A}(\alpha)$ and $\mathbf{B}(\beta)$ themselves.

Since a single associative and commutative operation can render many different operations, it is clear that in this trivial sense decomposability (9) is not unique. It is more interesting, however, to find out whether a response time $\mathbf{T}(\alpha,\beta)$ can be simultaneously ($\diamond$)-decomposed and ($\Diamond$)-decomposed (under one and the same stochastic relationship $\overset{s}{-}$) when $\diamond$ and $\Diamond$ are associative, commutative, and mutually nonrenderable. The answer to this question turns out to be negative, provided that the two operations are "well-behaved." Dzhafarov and Schweickert (1995) give the following sufficient (but not necessary) conditions for the "well-behavedness." First, $\diamond$ and $\Diamond$ belong to the class of *simple operations*, that consists of all *addition-like operations* $a \oplus b$ (i.e., those continuous in both arguments, strictly increasing in both arguments, and mapping onto their domains) and appended to them $min\{a, b\}$ and $max\{a, b\}$.[11] Second, the operations $\diamond$ and $\Diamond$ are *algebraically distinct*, which means that for any u and v, there is at most one unordered pair (x, y) such that $x \diamond y = u$ and $x \Diamond y = v$. These conditions are not very stringent: theoretically interesting competing decomposition rules are likely to be algebraically distinct simple operations. Under these conditions the decomposition rule uniqueness holds: the ($\diamond$)-decomposability excludes the ($\Diamond$)-decomposability, under the same $\overset{s}{-}$. In fact, this result follows from a yet stronger one according to which the ($\diamond$)-test and ($\Diamond$)-test for any two operations with postulated properties cannot be successful simultaneously under the same $\overset{s}{-}$.

The decomposition rule uniqueness does not imply any form of uniqueness for the time components. Generally, if a response time $\mathbf{T}(\alpha,\beta)$ is ($\diamond$)-decomposable under $\overset{s}{-}$, then one can find an infinity of the component times $\mathbf{A}(\alpha)$, $\mathbf{B}(\beta)$, into which this decomposition can be made. Nor does the decomposition rule uniqueness imply a form of uniqueness for the stochastic relationship. The latter should be treated as part of the time components' definition, and one can construct examples when $\mathbf{T}(\alpha,\beta)$ is both ($\diamond$)-decomposable under independence and ($\Diamond$)-decomposable under perfect positive interdependence (including the possibility that $\diamond$ and $\Diamond$ coincide).

[11] *Minimum* and *maximum* can be construed as limiting cases of addition-like operations. The results of Dzhafarov and Schweickert (1995) can be generalized to other limiting operations, but the extent of such a generalization is not quite clear.

An obvious but important consequence of the decomposition rule uniqueness is that decomposition (9) is an empirically falsifiable proposition rather than a descriptive characterization. If the four distributions of $\mathbf{T}(\alpha,\beta)$ in a 2×2 design are known precisely, and if the factor manipulations are found to be effective, then the decomposability can be verified or falsified for any decomposition rule and under either of the two forms of stochastic relationship. Moreover, in a list of simple operations that are pairwise algebraically distinct, all but at most one of them have to be rejected as true decomposition rules under a given form of stochastic relationship. When the distributions of $\mathbf{T}(\alpha,\beta)$ in a 2×2 design are only known on a sample level, one should expect that the difference between the two sequences in (11) or (12), depending on the form of $\overset{s}{-}$, will be small if $\diamond$ is the true decomposition rule and large if it is not. A sampling distribution theory for this difference (specifically, the Smirnov maximum distance between the empirical distribution functions) developed in Dzhafarov and Cortese (1996) allows one to formally test the hypothesis that a given operation is the true decomposition rule. In a Monte-Carlo simulation study Cortese and Dzhafarov (1996) evaluate the minimum size of the samples $\{\mathbf{T}_{ij}^1, .., \mathbf{T}_{ij}^n\}$ $(i = 1, 2, j = 1, 2)$ at which the true decomposition rule chosen from the "classical" list $\{+, min, max\}$ yields a reliably smaller difference between the two sequences in (11) or (12) than the remaining two operations. The results indicate that this minimum sample size is realistically achievable provided the effectiveness of the factor manipulations is sufficiently high[12]: the minimum sample size required is on the order of 10^3 under independence and on the order of 10^2 under perfect positive interdependence.

Returning to population-level considerations, a successful ($\diamond$)-test being a necessary condition for ($\diamond$)-decomposability (under the same form of $\overset{s}{-}$), a natural question arises as to whether this condition is also sufficient. Dzhafarov and Schweickert (1995) show that the answer to this question is affirmative for all simple operations under perfect positive interdependence: Under this stochastic relationship, if a ($\diamond$)-test is successful, then $\mathbf{T}(\alpha,\beta)$ is ($\diamond$)-decomposable (under the same relationship). With some technical qualifications, the same is true under independence for the operations *minimum* and *maximum*: If $\diamond$ is one of these two operations, then a successful ($\diamond$)-test under independence implies ($\diamond$)-decomposability under independence. For addition-like operations, however, this result does not hold. For instance, it is possible that the (+)-test under independence (i.e., the Ashby-Townsend-Roberts-Sternberg "summation test") is successful but that the response time cannot be additively decomposed into stochastically independent time components. Observe that due to the decomposition rule uniqueness, when this happens, the response time cannot be decomposed under independence by any other (algebraically distinct) operation either – in a sense, this response time is absolutely indecomposable into selectively influenced components.

[12] The construction of an effectiveness measure, that is, a measure of difference between $\{F_{12}(t), F_{21}(t)\}$ and $\{F_{11}(t), F_{22}(t)\}$ taken as unordered pairs (see Footnote 10), is a difficult and rather subtle issue that I will not discuss here. Obviously, if the factor manipulations are not effective at all, then the true decomposition rule cannot be distinguished from any other operation.

This concludes the discussion of the main results related to the problem of determining the decomposition rule under a known form of stochastic relationship. The reverse of this problem, determining the form of stochastic relationship under a known decomposition rule, appears substantially less tractable, even with as limited a choice as that between independence and perfect positive interdependence. Dzhafarov (1992) and Dzhafarov and Rouder (1996) propose a solution for a special case of this problem, based on an experimental design and theoretical assumptions very different from those discussed above. Suppose that α is the only factor in an experiment, and that it forms a "unidimensional strength continuum" with respect to some response time $\mathbf{T}(\alpha)$; that is, α is or can be transformed into a real-valued variable whose increase causes $\mathbf{T}(\alpha)$ to decrease in all quantiles. Consider an additive decomposition of $\mathbf{T}(\alpha)$ into an α-dependent and α-independent components (a unifactorial version of selective influence):

$$\mathbf{T}(\alpha) \stackrel{d}{=} \mathbf{A}(\alpha) + \mathbf{B}.$$

The results described below also apply to other addition-like operations because they can be transformed into addition by a monotonic transformation of the components (which would preserve both selectivity and stochastic relationship).

Using the asymmetric representation mentioned in Footnote 8, which here is more convenient than (7),

$$\{\mathbf{A}(\alpha),\mathbf{B}\} = \{A(\alpha, \mathbf{P}_1, \mathbf{P}_2), B(\mathbf{P}_2)\},$$

one can see that independence and perfect positive interdependence correspond to

$$\mathrm{A}(\alpha) \perp \mathbf{B} \Leftrightarrow A(\alpha, \mathbf{P}_1, \mathbf{P}_2) = A^\star(\alpha, \mathbf{P}_1),$$
$$\mathrm{A}(\alpha) \| \mathbf{B} \Leftrightarrow A(\alpha, \mathbf{P}_1, \mathbf{P}_2) = A^\star(\alpha, \mathbf{P}_2)$$

(in the latter case $A^\star$ is assumed to be increasing in the second argument).

It turns out that one can distinguish between these two possibilities if the following requirements are satisfied: as α increases, $A(\alpha, p_1, p_2)$ decreases and vanishes for any pair of values p_1, p_2 of $\mathbf{P}_1, \mathbf{P}_2$, and it vanishes with asymptotically proportional rates for any two such pairs (p_1, p_2) and $(p_1^\star, p_2^\star)$. It can be proved then that

$$T_p(\alpha) = B_p + \Gamma(p)s(\alpha) + o\{s(\alpha)\}, \tag{13}$$

where $T_p(\alpha)$ and B_p are the rank-p quantiles $(0 < p < 1)$ of $\mathbf{T}(\alpha)$ and $\mathbf{B}$, respectively, $s(\alpha)$ is a strictly decreasing and vanishing positive function, and $\Gamma(p)$ is a coefficient such that

$$\mathbf{A}(\alpha) \perp \mathbf{B} \Leftrightarrow \Gamma(p) \equiv const$$
$$\mathbf{A}(\alpha) \| \mathbf{B} \Leftrightarrow \Gamma(p) \text{ increases in } p.$$

The transformation $s(\alpha)$ can be evaluated in several ways (Dzhafarov, 1992), but one can circumvent this problem altogether by observing that $s(\alpha)$ in (13) can be replaced with any asymptotically linear transformation thereof, and that $T_p(\alpha)$ for a fixed rank p or some average $T_\bullet(\alpha)$ of $T_p(\alpha)$ across a certain interval of ranks present observable examples of such linear transformations. Thus plotting $T_p(\alpha)$ against $T_\bullet(\alpha)$ one gets

$$T_p(\alpha) = \left[B_p - \frac{\Gamma(p)}{\Gamma_\bullet} B_\bullet\right] + \frac{\Gamma(p)}{\Gamma_\bullet} T_\bullet(\alpha) + o\{s(\alpha)\},$$

where the subscript dots indicate averaging across some interval of quantile ranks. The result is that the tangent lines drawn to several $T_p(\alpha)$-versus-$T_{\bullet}(\alpha)$ curves at progressively smaller values of $s(\alpha)$ (i.e., progressively higher values of α) tend to a parallel pattern of unit-slope lines under independence and to a diverging fan pattern, with slopes changing from below unity to above unity, under perfect positive interdependence. Dzhafarov and Rouder (1996) show how this prediction can be converted to a practical test, when $\mathbf{T}(\alpha)$ are only known on a sample level and only for several distinct values of α.

5. Possible developments

Here, I mention a few directions of research that seem to stem naturally from the discussion above.

(A) *A physicalist account of selectively influenced interacting processes.* Representation (6) is obviously too flexible, and it is desirable to have a systematic way of subjecting it to restrictions that could lead to general but falsifiable theories. One possible approach consists in treating all interactions between processes as local in time, so that changes in the levels of the processes at a given moment only depend on the characteristics of these processes (levels, velocities, accelerations, etc.) at the same moment. This approach leads to differential equations of the form

$$\dot{R}_1(t) = r_1[\alpha, R_1(t), R_2(t), \dot{R}_2(t), \ddot{R}_1(t), \ddot{R}_2(t), ...]$$
$$\dot{R}_2(t) = r_2[\beta, R_2(t), R_1(t), \dot{R}_1(t), \ddot{R}_2(t), \ddot{R}_1(t), ...]$$

subject to certain initial conditions. The levels of the processes in such a representation may be defined in terms of their quantile ranks in relation to their respective criteria, or on scales calibrated by a specific choice of the criteria.

(B) *Decompositions into more than two components.* Even with only two factors involved, the general form of the response time decomposition into selectively influenced components is not (5) but rather

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} \mathbf{A}(\alpha) \diamond \mathbf{B}(\beta) \Diamond \mathbf{C} = A(\alpha,\mathbf{P}_1, \mathbf{P}_2, \mathbf{P}_3) \diamond B(\beta,\mathbf{P}_1, \mathbf{P}_2, \mathbf{P}_3) \Diamond C(\mathbf{P}_1, \mathbf{P}_2, \mathbf{P}_3),$$

with some order of the operations implied. The Dzhafarov-Schweickert decomposition tests allow one to recover some such decompositions under perfect positive interdependence of all three components. For instance, in the decomposition

$$\mathbf{T}(\alpha,\beta) \stackrel{d}{=} max\{\mathbf{A}(\alpha),\mathbf{B}(\beta)\} + \mathbf{C},$$

if $\mathbf{A}||\mathbf{B}||\mathbf{C}$, then the operation *max* can be recovered by the (*max*)-test under perfect positive interdependence, because the right-hand expression is $max\{\mathbf{A}(\alpha)+\mathbf{C}, \mathbf{B}(\beta)+\mathbf{C}\}$ and $\mathbf{A}(\alpha)+\mathbf{C}||\mathbf{B}(\beta)+\mathbf{C}$. Such a recovery is not possible, however, if $\mathbf{A}\perp\mathbf{B}\perp\mathbf{C}$, because then $\mathbf{A}(\alpha)+\mathbf{C}$and $\mathbf{B}(\beta)+\mathbf{C}$ are interdependent in a complex way. Although partial results in dealing with this and similar problems are available (Colonius & Vorberg, 1994; Townsend & Nozawa, 1995), it is yet to be seen whether some generalizations of the Dzhafarov-Schweickert tests can be developed for at least three-component decompositions $\mathbf{A}(\alpha)\diamond\mathbf{B}(\beta)\Diamond\mathbf{C}$ or $\mathbf{A}(\alpha)\diamond\mathbf{B}(\beta)\Diamond\mathbf{C}(\gamma)$ under stochastic independence.

(C) *Decompositions under other forms of stochastic relationship.* Dealing with stochastic relationships other than independence and perfect positive interdependence is arguably the most challenging problem in the context of time decompositions. Existence and uniqueness properties of decompositions such as

$$\mathbf{T}(\alpha,\beta) \overset{d}{=} A(\mathbf{P}_1,\mathbf{P}_2) \diamond B(\beta,\mathbf{P}_1,\mathbf{P}_2)$$

remain unknown if one imposes no or only mild constraints on the form of the functions A and B and on the decomposition rule $\diamond$. It is possible that not very much can be achieved in this direction, and the abstract algebraic approach of Dzhafarov and Schweickert (1995) will have to be eventually abandoned in favor of recovering architectures of selectively influenced interacting processes, perhaps along the "physicalist" lines suggested earlier in this section. It is also possible that the two simplest forms of stochastic relationship considered in this chapter will prove to be sufficient for describing a good deal of empirical data, perhaps in conjunction with strict limitations imposed on the shape of response time distributions. It would be highly beneficial, therefore, to develop powerful techniques for determining, at least in very simple situations, whether independence or perfect positive interdependence is truly present, as opposed to choosing between them under the assumption that one of them holds.

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