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The *P* system: A scheme for organizing Pavlovian procedures

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The present paper introduces the *P* system as a scheme for organizing Pavlovian procedures in an orderly and comprehensive manner. The system is defined by three temporal variables and three restrictions on their possible values. It can be used to define all standard temporal variables—namely, stimulus duration, interstimulus interval, trace interval, and intertrial interval—as well as variables C and T of scalar expectancy theory. The system also permits the definition of new independent variables through combinations of the basic temporal parameters. We exemplify this possibility by defining two ratios of temporal intervals. These ratios lead to a space where traditional Pavlovian arrangements (viz., simultaneous, forward-trace, forward-delay, backward) become points on a continuum, and optimal conditions across different experimental preparations become equivalent. Finally, the system can be used to define contingency variables such as p(US/CS), p(US/~CS), and the phi coefficient (ϕ). In this manner, an organization of different kinds of Pavlovian procedures is achieved on the basis of a single parametric scheme. Such an organization facilitates establishing procedural and theoretical relationships between temporal and contingency variables. The paper concludes with a discussion of certain limitations of the system and other related issues

An essential feature of experimental science is the definition and implementation of procedures, explicit operations for discovering functional relations in a systematic manner. In its most general form, a procedure involves selecting and defining certain variables that are considered as necessary and sufficient conditions for a particular phenomenon of interest, according to some hypothesis or theory. The present paper focuses on two kinds of independent variables in Pavlovian conditioning research—namely, temporal and contingency.

Standard temporal variables involve the definition of time intervals between the onsets and offsets of different kinds of environmental events or stimuli. Such variables include stimulus duration, the interstimulus interval (ISI), the trace interval (TI), and the intertrial interval (ITI). Contingency variables involve the definition of probabilities of occurrence of certain kind of stimulus in the presence or absence of another kind. Disagreements exist regarding the relative importance of each kind of variable as the critical determinant of Pavlovian conditioning (e.g., Cooper, 1991; Damianopoulos, 1982; Gibbon & Balsam, 1981; Gormezano & Kehoe, 1975, 1981; Jenkins, 1984; Miller & Grahame, 1991; Papini & Bitterman, 1990; Rescorla, 1972; Rescorla & Wagner, 1972). Yet the evidence shows that both kinds of variables have systematic effects on behavior. Such effects are expressed through functional relations that currently constitute the empirical content of Pavlovian conditioning research.

Temporal and contingency variables lead to the definition of different kinds of Pavlovian procedures and, hence, the discovery of different kinds of functional relations. For example, manipulating the ISI while keeping stimulus probabilities constant is operationally very different from manipulating these probabilities while keeping the ISI constant. And the resulting functional relations (viz., ISI vs. contingency functions, respectively) are very different as well. In addition to the theoretical issue of whether or not these differences represent expressions of a single associative mechanism (e.g., Damianopoulos, 1987), they pose the methodological issue of how different kinds of Pavlovian procedures are to be organized. The main motivation of the present paper is to address this issue.

Our main objective is to introduce the *P* system as a scheme for organizing different kinds of Pavlovian procedures in an orderly and comprehensive manner. In the first section, we provide a description of the system. In the second section, we apply the system to the definition of standard temporal variables, and we exemplify how the

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system's parameters can be combined to define new variables that possess certain organizing properties. In the third section, we apply the system to the definition of contingency variables. We conclude the paper by discussing certain limitations of, and certain issues raised by, the system.

THE *P* SYSTEM

The *P* system is defined by three temporal variables and three restrictions on their possible values. As Figure 1 shows, the variables are a time cycle (t), the interval between the onset of t and the onset of a given stimulus i (b_i), and the interval between the onset of t and the offset of i (e_i). The letters b and e stand for "begin" and "end," respectively.

Possible values of the above variables are restricted as follows: (1) t must be greater than zero, (2) b_i must be equal to or greater than zero, but less than e_i, and (3) e_i must be equal to or less than t. Restriction 2 stipulates that b_i cannot take negative values, nor can it take values greater than or equal to e_i. Giving b_i a value smaller than e_i ensures consistency with the fact that a stimulus must begin before it ends. Restriction 3 does not allow the offset of i to go beyond t. Combined, Restrictions 2 and 3 ensure that the onset of i does not coincide with the end of t.

Subscript i designates a stimulus *class* defined in terms of physical properties, such as modality (e.g., tone, light, shock, food, etc.), submodality (e.g., red-light, blue-light, etc.), and intensity (e.g., decibel, lux, mA, etc.). Accordingly, a subscript can be replaced by any convenient label designating a stimulus class, such as CS (for conditional stimulus), US (for unconditional stimulus), tone, shock, and so on. A stimulus *instance* represents the occurrence of a member of a stimulus class. The class–instance distinction helps us to avoid ambiguities in using the term *stimulus*. Indeed, suppose that a rat was given five shocks in a session. We could say that there were a total of five stimuli in that session or that *shock* was the stimulus used in the session. To avoid this kind of ambiguity, we can make the class–instance distinction explicit and say, in that case, that the animal was given five instances of the stimulus class *shock*.

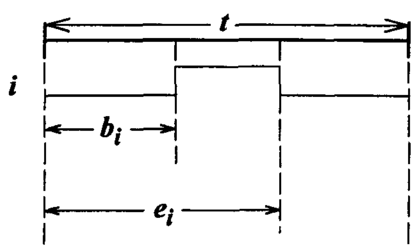

Figure 1. The *P* system is defined by a time cycle (t), the interval between the onset of t and the onset of an instance of stimulus class i (b_i), and the interval between the onset of t and the offset of that instance (e_i).

Variable t represents an external basic period for the occurrence of stimuli. Hence, t provides an explicit relative zero point that is defined independently of stimulus onsets and offsets. This variable is conceptually similar to parameters T and τ of the t–τ systems (Schoenfeld & Cole, 1972), a scheme for organizing operant conditioning procedures. In the spirit of these systems, t represents a unit of analysis of session time. Such a unit is independent of the occurrence of any environmental or behavioral event. Dividing session time into arbitrary, noncued units as a general strategy in Pavlovian procedures has been proposed before (Prokasy, 1965) and adopted in a number of experiments (e.g., Gamzu & Williams, 1971, 1973; Jenkins & Lambos, 1983; Lindblom & Jenkins, 1981; Rescorla, 1968, 1969). In such cases, time units serve as trials for the probabilistic occurrence of instances of a stimulus class (typically, a US). In contrast, our t cycle serves only as a first variable for the definition of other temporal variables (viz., b and e).

In Pavlovian conditioning procedures, t may be seen as a unit of analysis of context-exposure time in a session. Its only purpose is to serve as a temporal framework for defining unequivocally stimulus onsets and offsets in a completely context-dependent manner. Thus, b_i tells us how much context-exposure time has elapsed from the onset of a t cycle to the onset of a given stimulus i, whereas e_i tells us how much context-exposure time has elapsed from the onset of a t cycle to the offset of i. In this manner, e_i includes i-exposure time as part of context-exposure time. Such an inclusion is consistent with the idea of "embeddedness" of context levels in a hierarchical conceptualization of the structure of contexts in Pavlovian conditioning (see Balsam, 1984a).

The central claim we shall develop in the following sections is that all standard Pavlovian conditioning variables can be derived from or defined in terms of the *P* system. It is through this derivation that, we believe, the system may be useful to provide Pavlovian procedures with an organic structure, to systematize them according to a common set of basic parameters. In addition to this capability, the system is maximally open to allow for the definition of new variables through combinations of the three basic parameters.

In the rest of the paper, we elaborate and illustrate these claims. For our present purposes, we concentrate on applications that involve three additional restrictions. Nothing in the system, as defined above, requires us to adopt such restrictions. However, they represent convenient simplifications that allow for a better appreciation of the system's organizing capabilities. First, we shall restrict applications to the occurrence of only one instance per stimulus class per t cycle. Second, we will restrict multiple-trial applications to sequences of nonoverlapping t cycles, such that the onset cycle coincides with the offset of the immediately preceding cycle. Third, in the case of several t cycles, we shall assume that the value of t, as well as the values of b and e for a particular stimulus class, remain constant from cycle to cycle within and across sessions for any given experimental condition. Of course, t may differ from one experimental condition to the other, and b and e may differ across stimulus classes as well as experimental conditions.

The additional restrictions are graphically represented in Figure 2. It is convenient to view this representation as a segment of a session of an experimental group or condition in a hypothetical study. The horizontal dimension represents the t cycles (labeled as t_n, t_{n+1}, and t_{n+2}), and the vertical dimension represents the stimulus classes (labeled as i, j, and k). The dots represent other t cycles and other stimulus classes. Only one instance per stimulus class occurs for any t cycle. However, instances of several stimulus classes may occur within a given cycle—in which case, such instances have this cycle in common. The value of t remains constant throughout the session for all stimulus classes. Instances of each stimulus class occur within a t cycle according to the values of b and e assigned for that class, which also remain constant throughout the session, although they may be different from one stimulus class to the other. In the t cycles shown, for example, $b_i < b_j$, $b_i > b_k$, $b_j = e_k$, and so on. Each particular value, however, remains constant across t cycles. A session may consist of one or more t cycles, on the basis of which we can define one- or multiple-trial procedures, respectively.

DEFINING STANDARD TEMPORAL VARIABLES

The P system can be used to define algebraically all standard temporal variables studied through Pavlovian procedures—namely, stimulus duration, ISI, TI, and ITI. Let us take each variable in turn.

To define stimulus duration in terms of the P system, we can assign values to b and e for one stimulus class i representing either a CS or a US. The duration of instances of i, then, is given algebraically by $e_i - b_i$ (see Figure 3a). To define the ISI and TI, we assign values to b and e for two stimulus classes—typically, a CS and a US. The ISI is typically defined as the time between the CS onset and the US onset (Kamin, 1965), which is given by $b_{US} - b_{CS}$. This difference results in positive values for forward procedures (see Figure 3b), zero for simultaneous procedures, and negative values for backward procedures. The TI is typically defined as the time between CS offset and US onset, which is given by $b_{US} - e_{CS}$. This difference results in positive values for forward procedures (see Figure 3c) and negative values for backward procedures. Alternatively, TI can be defined as the time between US offset and CS onset, which is given by $e_{US} - b_{CS}$. This difference results in negative values for forward procedures and positive values for backward procedures. Finally, the ITI is typically defined as the time from the offset of an instance of a CS to the onset of the next instance. If the CS occurs in every t cycle (see Figure 3d), then the ITI is given by $t - (e_{CS} - b_{CS})$. Later we show how to derive mean ITI values in contingency procedures, where the CS occurs only in some t cycles.

In addition to the above variables, the P system allows for a definition of variables C and T of the scalar expectancy theory (SET; Gibbon & Balsam, 1981). In the simplest case, a CS and a US occur in all t cycles, and ISI > 0. C is defined as "the time from the offset of one reinforcer to the onset of the next" (Gibbon & Balsam, 1981, p. 229), which is given in the P system by $t - (e_{US} - b_{US})$, the interreinforcement interval. T is operationally defined as the total amount of CS-exposure time between successive reinforcements, which depends on TI (Balsam, 1984b; Kaplan, 1985). In the simplest case, we can assume that CS instances are paired with US instances in all t cycles. If TI ≤ 0, then T is identical to the ISI. If TI > 0, then T is identical to CS duration. Here, TI, ISI, and CS duration can be defined in terms of the P system, as shown before. Later, we provide definitions of C and T in contingency procedures.

DEFINING NEW VARIABLES

The P system allows for the definition of new variables through combinations of the basic parameters t, b, and e. For example, we can define stimulus duration relative to context-exposure time, which is given by $(e_i - b_i)/t$. This ratio provides a measure of the extent to which stimulus instances represent tonic or phasic cues. Indeed, as the ratio tends toward 1, instances of i become more tonic (or less phasic). If the ratio is equal to 1, then i can be effectively regarded as a tonic or contextual cue. As the ratio

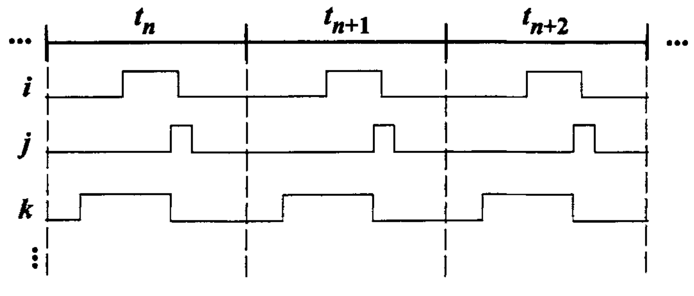

Figure 2. Representation of a generic session, according to the P system. The t cycle functions as a unit of analysis of context-exposure time in a session.

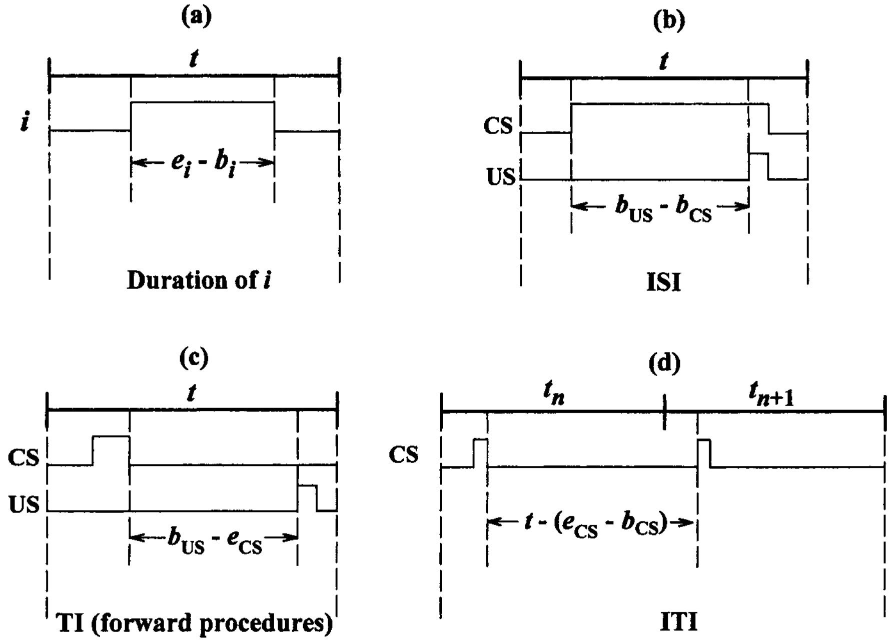

Figure 3. Derivation of standard temporal variables from the *P* system. (a) Stimulus duration. (b) Interstimulus interval (ISI). (c) Trace interval (TI) for forward procedures. (d) Intertrial interval (ITI).

tends to zero, instances of i become less tonic (or more phasic). In this manner, the tonic–phasic dichotomy becomes a continuum.

As another example, we want to define two ratios—S_b and S_e—which are relatively simple and possess interesting organizing properties. These two ratios represent only examples of how t, b, and e can be combined to define new variables. Hence, strictly speaking, S_b and S_e are not part of the P system, but only two among the possible variables that can be derived from the system.

The S_b ratio is the fraction of a t cycle occupied by the ISI, whereas the S_e ratio is the fraction of a t cycle occupied by $e_{US} - e_{CS}$. Formally,

$$S_b = (b_{US} - b_{CS})/t, \quad (1)$$

and

$$S_e = (e_{US} - e_{CS})/t. \quad (2)$$

Given the restrictions described earlier, possible values of S_b and S_e are confined to the interval $[-1,1]$. Subtracting the US parameters from the CS ones in Equations 1 and 2 allows for a more useful organization of procedures. We can use S_b and S_e to define a square where procedures can be represented visually. For convenience, we call it the S square. Figures 4, 5, and 6 show some explorations of this space. In all the figures, S_b is represented in the horizontal axis, whereas S_e is represented in the vertical axis. The S_b and S_e values, as well as the wave representations corresponding to each plot, are shown.

Figure 4 shows an exploration where S_b is manipulated by changing b_{CS}, while keeping t, e_{CS}, b_{US}, and e_{US} constant. This exploration thus involves a simultaneous manipulation of CS duration, ISI, and ITI. Because the CS and US end at the same time, $S_e = 0$ for all procedures. In general, procedures in which the CS and US coterminate are represented by the horizontal line that intersects point (0,0), the center of the S square. This point represents arrangements in which CS and US begin and end concurrently.

In Figure 5, S_b and S_e are manipulated by changing only t. This exploration thus involves a manipulation of ITI. Note that manipulations of S_b and S_e by changing t alone involve moving a point along a line that intersects the origin. As t increases, everything else being equal, both S_b and S_e tend toward zero. As t decreases, S_b and S_e will tend toward -1 or 1, depending on the values of b_{CS}, e_{CS}, b_{US}, and e_{US}. Also, because the CS and US had the same durations, the values of S_b and S_e were identical for all plots. In general, S_b and S_e will take the same value if CS and US have the same duration.

Finally, Figure 6 shows an exploration in which S_b and S_e are manipulated by changing b_{US} and e_{US}, while keeping t, b_{CS}, and e_{CS} constant. These manipulations involve moving the US within t cycles and, hence, manipulating simultaneously ISI and TI while keeping constant stimulus durations and ITI. Note that Plots (.7,.5), (.2,0), (0,−.2), and (−.25,−.45) represent forward-trace, forward-delay, simultaneous-onset, and backward-trace arrangements, respectively. Traditional Pavlovian arrangements thus become points on a continuum. In general, arrangements where $0 < S_b < 1$, $S_b = S_e = 0$, or $-1 < S_b < 0$ represent forward, simultaneous, or backward procedures, respectively. Also, for all the plots, S_b was greater than S_e because CS duration was greater than US duration.

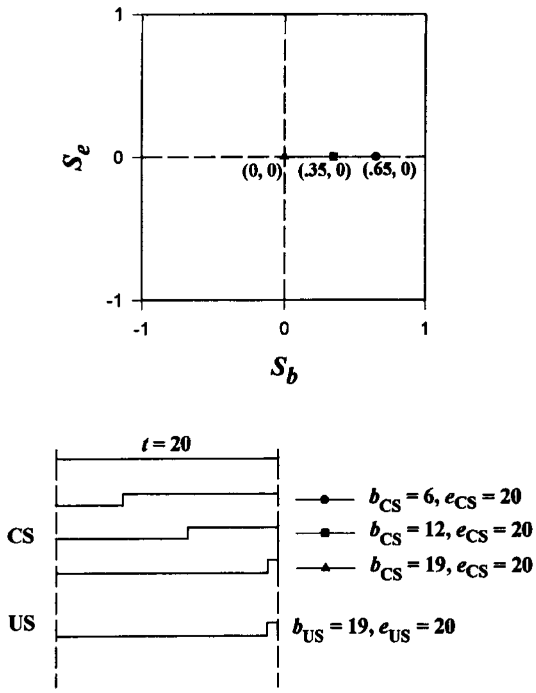

Figure 4. Exploration of the S square in which S_b is manipulated by changing b_{CS}. Each plot represents an experimental condition whose sessions consist of several t cycles of the same type. The values of t, e_{CS}, b_{US}, and e_{US} were kept constant. The values of S_b and S_e are shown within the graph. Parameters and square-wave representations for each condition are shown underneath the graph.

The last exploration shows that a description of traditional arrangements in terms of S_b and S_e refers to what occurs within t cycles. Hence, it seems sufficient to look at one t cycle to determine what kind of arrangement is in effect. This consideration, however, must be qualified, given the possibility of scheduling several t cycles. Strictly speaking, to say that a particular arrangement is in effect, we must assume that sessions consist only of t cycles where a CS and a US occur. If sessions include CS-alone and/or US-alone t cycles, a given arrangement is in effect only for some t cycles, but not for others. For the moment, we adopt the assumption and leave these considerations for the next section.

Another organizing possibility of S_b and S_e relates to a description of optimal circumstances for excitatory conditioning across Pavlovian preparations. For this application, we chose three standard preparations: nictitating membrane response (NMR) in rabbits (Gormezano, Schneiderman, Deaux, & Fuentes, 1962), autoshaped keypeck in pigeons (Brown & Jenkins, 1968), and conditioned suppression (CER) in rats (Estes & Skinner, 1941). It is known that optimal values of temporal variables vary widely across these preparations. For NMR, the optimal ISI is between 0.2 and 0.4 sec (Frey & Ross, 1968; Smith, Coleman, & Gormezano, 1969), the optimal ITI is approximately 20 sec (Smith et al., 1969), and the optimal shock duration is about 0.1 sec (Tait, Kehoe, & Gormezano, 1983). For autoshaping, the optimal ISI is about 4 sec, the optimal food-access time is approximately 4 sec, and the optimal ITI is about 96 sec (Gibbon, Baldock, Locurto, Gold, & Terrace, 1977). For the CER preparation, the optimal ISI is around 20 sec (Libby, 1951; Yeo, 1974), the optimal shock duration is about 1 sec (Riess & Farrar, 1973), and the optimal ITI is approximately 360 sec (Libby, 1951).

We can assign values to t, b, and e such that they lead, on the one hand, to values reasonably similar to the optimal ones given in the preceding paragraph and, on the other, to the same pair of S_b and S_e values for the three preparations. Table 1 shows the selected values of t, b, and e for each preparation. Table 2 shows the derived ISI, US duration, and ITI. The values in parentheses show the experimental optimal values given above. For simplicity, it is assumed that a forward-delay arrangement is in effect and that the CS and US coterminate. All the durations are given in seconds. Applying Equations 1 and 2 to the values given in Table 1, we have that $S_b = .025$, and $S_e = 0$, for the three preparations. In this manner, NMR, autoshaping, and CER become equivalent regarding optimal circumstances for excitatory conditioning.

This kind of invariance also applies to a particular preparation. Indeed, an infinite number of combinations of t, b, and e values may produce the same pair of S_b and S_e values even if we use the same preparation. For example, consider an experiment where $S_b = .05$, using NMR. This value is determined by infinitely many values of t, b, and e (e.g., $t = 10$ sec, $b_{CS} = 5$ sec, and $b_{US} = 5.5$ sec; or $t = 100$ sec, $b_{CS} = 50$ sec, and $b_{US} = 55$ sec; or $t = 200$ sec, $b_{CS} = 100$ sec, and $b_{US} = 110$ sec; and so on). The same applies to S_e. This possibility implies that, if we want to consider S_b and S_e as predictive variables, the same point in the S square should have the same effect on the dependent variable, regardless of the specific t, b, and

Table 1
Sample of *P*-System Parameters for NMR, Autoshaping, and CER

	NMR	Autoshaping	CER
t	20	120	600
b_{CS}	10	84	250
e_{CS}	10.6	90	266
b_{US}	10.5	87	265
e_{US}	10.6	90	266

Note—For all procedures, $b_{CS} < b_{US}$, and $e_{CS} > b_{US}$ (i.e., a forward-delay procedure is in effect).

Table 2
Optimal ISI, US Duration, and ITI Values Computed From the Parameters Shown in Table 1

	NMR	Autoshaping	CER
ISI	0.5 (0.4)	3 (3)	15 (20)
US duration	0.1 (0.1)	3 (3)	1 (1)
ITI	19.4 (20)	114 (96)	584 (360)

Note—Experimentally determined values are in parentheses.

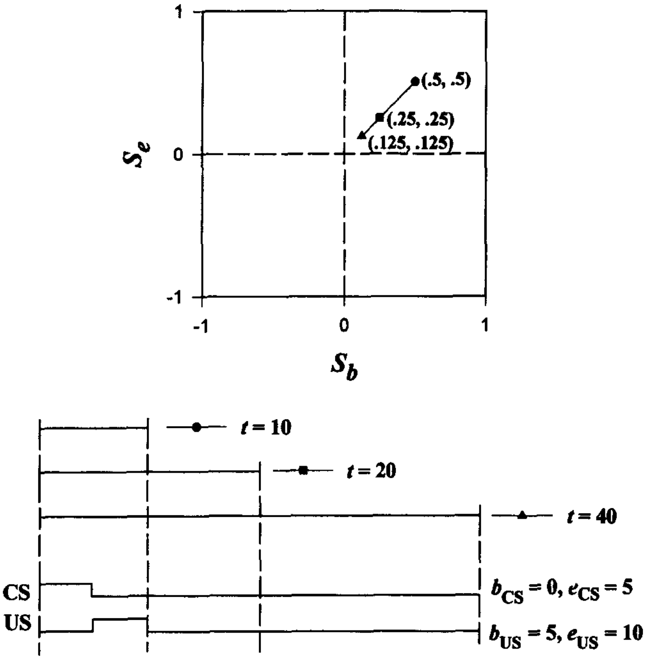

Figure 5. Manipulation of *t*. Each plot represents an experimental condition whose sessions consist of several *t* cycles of the same type. As *t* increases, S_b and S_e tend toward zero, everything else being equal.

e values that determine such a point. An exploration of such invariances, using the same preparation, could represent a first experimental characterization of the *S* square.

The C/T ratio of SET shows similar invariances. Indeed, Table 3 shows the C and T values computed from the parameters given in Table 1 for each preparation. Table 3 also includes the expected number *n* of trials before acquisition, as predicted by Gibbon and Balsam (1981, p. 241, Equation 1). Note that the values of C/T and *n* are very similar across preparations. These computations show that S_b and S_e are like C/T in that they lead to invariances between and within preparations.

We showed how to define standard temporal variables in terms of the *P* system. We also exemplified, through the definition of ratios of temporal intervals, how the basic parameters *t*, *b*, and *e* can be combined to define new variables that possess certain organizing properties. Let us now show how contingency variables can be derived from the *P* system and how such a derivation facilitates establishing relationships between temporal and contingency variables.

Table 3
C and T Values Computed From the Parameters Shown in Table 1

	NMR	Autoshaping	CER
C	19.9	113	599
T	.5	3	15
C/T	39.8	37.67	39.93
n	7.66	8.11	7.64

Note—The value of *n* represents the expected number of reinforced trials before acquisition, as predicted by Gibbon and Balsam (1981, p. 241, Equation 1).

DEFINING CONTINGENCY VARIABLES

The study of contingency variables represents a relatively more recent trend in Pavlovian conditioning research (e.g., Gamzu & Williams, 1971, 1973; Rescorla, 1966, 1967, 1968; Rescorla & LoLordo, 1965). In this section, we show how such variables can be derived from the *P* system. The first step is to specify an event that allows for an unequivocal definition of stimulus probabilities. The simplest strategy is to identify the occurrence of any stimulus with the occurrence of its onset within a *t* cycle. In general, then, an instance of a stimulus class *i* may occur within a *t* cycle starting at the end of b_i with some probability. Here, the onset of an instance of *i* within a *t* cycle becomes conditional upon whether or not b_i has elapsed. We can thus define the probability of occurrence of an instance of a stimulus class *i* as the conditional probability of its onset, given that b_i has elapsed, or $p(i \text{ onset} \mid b_i)$. This probability can be abbreviated as $p(i)$. The probability of nonoccurrence of the onset of *i* given that b_i has elapsed is the complement of $p(i)$, or $p(\sim i \text{ onset} \mid b_i)$. This probability can be abbreviated as $p(\sim i)$ and is equal to $1 - p(i)$.

If $p(i) = 1$, then succesive instances of *i* are separated by a constant interval (ITI in the case of a CS, or the interreinforcement interval in the case of a US), which defines a fixed-time procedure. In contrast, if $p(i) < 1$, in-

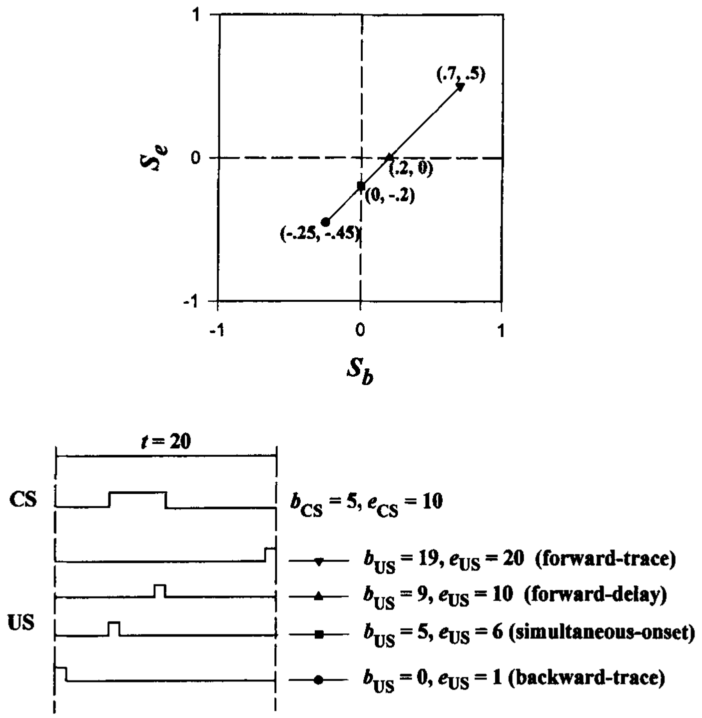

Figure 6. Manipulation of b_{US} and e_{US}, showing that the classification of traditional Pavlovian arrangements (i.e., forward-trace, forward-delay, etc.) becomes a continuum in the S square. Each plot represents a hypothetical experimental condition whose sessions consist of several t cycles of the same type.

stances of i would not occur at every t cycle and, hence, will be separated by different intervals. This strategy produces a random-time procedure. In both types of procedures, the expected inter-i interval is given by $[t - (e_i - b_i)]/p(i)$. Also, the expected number of instances of i in a session is given by $p(i) \cdot n$, where n is the number of t cycles constituting the session.

By replacing i with standard labels, we can define variables such as p(US), p(US | CS), and p(US | ~CS), which are given in the P system by p(US onset | b_{US}), p[(US onset | b_{US}) | (CS onset | b_{CS})], and p[(US onset | b_{US}) | (~CS onset | b_{CS})], respectively. From these variables, we can define negative, zero, and positive contingency procedures. We can also write C = $[t - (e_{US} - b_{US})]/p(\text{US})]$, and T = $(e_{CS} - b_{CS})/p(\text{US}\,|\,\text{CS})$, to define the C and T variables of SET so that intermittent-pairing procedures are included.

Identifying the occurrence of a stimulus instance with its onset in a t cycle allows us to give an operational interpretation of the conditional expression "US|CS." Traditionally, this expression designates a relation of the form "If CS, then US," or "US occurrence, given CS occurrence." In the present scheme, "CS occurrence" signifies "CS-onset occurrence," whereas "~CS" signifies "CS-onset nonoccurrence," both events corresponding to the end of b_{CS}. Similarly, "US" and "~US" signify "US-onset occurrence" and "US-onset nonoccurrence," respectively, both events corresponding to the end of b_{US}. Finally, "given" signifies that CS onset occurs before US onset (i.e., a forward arrangement is in effect). Therefore, US | CS signifies "US-onset occurrence, given CS-onset occurrence." In terms of the P system, "given" signifies that $b_{CS} < b_{US}$.

The above definitions allow us to apply the basic strategy proposed by Gibbon, Berryman, and Thompson (1974) to the derivation of a contingency measure from the P system. In the spirit of that strategy, we can classify the t cycles of a session into the categories of a fourfold contingency table: "CS & US" (t cycles where a CS and a US occur), "CS & ~US" (CS-alone t cycles), "~CS & US" (US-alone t cycles), and "~CS & ~US" (t cycles where no CS and no US occur). The sizes of these categories, as measured by the number of cases, can be labeled as A, B, C, and D, respectively. On this basis, we can use the standard phi coefficient (ϕ) equation for 2 × 2 contingency tables:

$$\phi = \frac{AD - BC}{\sqrt{(A+B)(C+D)(A+C)(B+D)}}. \qquad (3)$$

Like the possible values of S_b and S_e, the possible values of ϕ are confined to the $[-1,1]$ interval. Negative contingency procedures correspond to arrangements where $-1 \leq \phi < 0$. The noncontingent procedure corresponds to the case where $\phi = 0$. And positive-contingency procedures correspond to arrangements where $0 < \phi \leq 1$.

In contrast to the equations presented by Gibbon et al. (1974, pp. 590-591), Equation 3 does not include—and, hence, is not sensitive to—the manipulation of temporal variables. Such an exclusion raises the issue of how temporal and contingency variables can be related using the *P* system. At least three strategies are possible in this respect. First, we could incorporate t, b_{CS}, b_{US}, e_{CS}, and e_{US} separately into Equation 3. Second, we could incorporate such variables as S_b and S_e into Equation 3. Third, we could attach ϕ to the *S* square and obtain a three-dimensional space. The first and second strategies lead to one descriptive dimension, for which they are more parsimonious than the third one. However, the third strategy seems more appropriate at the present moment to show some of the organizing properties of variables derived from the *P* system.

Figure 7 shows the ϕ_S cube, a space that results from attaching ϕ to the *S* square. The organizing properties of the ϕ_S cube can be illustrated by showing the same exploration of the *S* square depicted in Figure 6 for three values of ϕ: 1 (explicitly paired procedure), 0 (noncontingent procedure), and -1 (explicitly unpaired procedure). As discussed earlier, Figure 6 shows manipulations of S_b and S_e such that traditional Pavlovian arrangements become points on a continuum. We have said that a derivation of these arrangements from S_b and S_e is meaningful only in reference to "CS & US" t cycles. We also assumed that sessions consisted only of such t cycles. Now, we can formulate this assumption more precisely by saying that it corresponds to the exploration in Figure 7, where $\phi = 1$. Here, we can say that a particular traditional arrangement is *completely* in effect. In contrast, when $\phi = 0$, we can only say that a particular arrangement is *partially* in effect, because "~CS & US" and "CS & ~US" t cycles also occur, which do not allow for a specification of traditional arrangements. Finally, when $\phi = -1$, no traditional arrangement is in effect, since only "CS & ~US" and "~CS & US" t cycles occur. These explorations lead

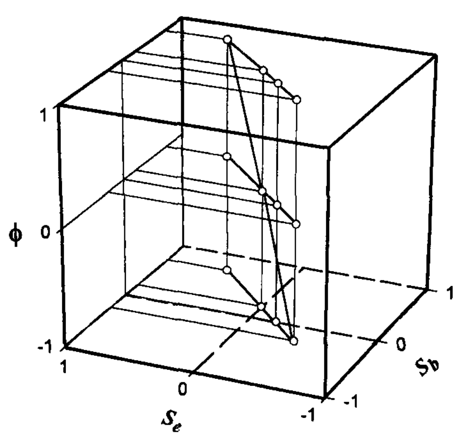

Figure 7. The ϕ_S cube, a space that results from attaching ϕ to the *S* square. The same exploration of the *S* square shown in Figure 6 is now shown for three values of ϕ—namely, 1, 0, and -1—which correspond to explicitly paired, noncontingent, and explicitly unpaired procedures, respectively.

to a plane that cuts through the ϕ_S cube and whose diagonal represents manipulations of temporal and contingency variables.

CONCLUDING REMARKS

We have shown how the *P* system serves as a common parametric foundation for defining different kinds of variables and, hence, organizing different kinds of Pavlovian procedures in an orderly and comprehensive manner. The organizing possibilities of the system arise from its openness to allow for a derivation of temporal and contingency variables. The system also permits, through combinations of the basic parameters, the definition of new variables that posses certain organizing properties. We exemplified this feature in terms of two ratios of temporal intervals (viz., S_b and S_e). This possibility leads to a large class of unexplored procedures, thus conferring a heuristic value to the system. To conclude the paper, we want to discuss certain issues that are raised by the system. We have divided them into intrinsic limitations of the system as an organizing scheme and other issues.

Intrinsic Limitations

A first limitation is that the system does not permit an organization of Pavlovian procedures that involve manipulations of stimulus intensity and modality, which have been shown to be strong determinants of conditioning (e.g., Annau & Kamin, 1961; Garcia & Koelling, 1966; Gormezano, 1972; Jenkins & Moore, 1973; Kamin, 1965; Pavlov, 1927; Randich & Rescorla, 1981; Revusky, 1968; Sherman, 1978). Strictly speaking, then, the *P* system represents a scheme only for organizing Pavlovian procedures that involve manipulations of temporal and/or contingency variables.

A second limitation arises in relation to procedures that involve preparations in which t, b, and/or e cannot be specified unequivocally. The typical example of this kind of preparation is taste aversion. In this preparation, training takes place in the animal's cage, where it is nearly impossible to specify CS and US onsets and offsets. Similar difficulties arise in behavioral pharmacology studies. In general, then, procedures that involve these kinds of preparations cannot be organized through the *P* system. One could argue that autoshaping presents similar difficulties regarding US onset and offset: It is unclear exactly at what point food exerts its unconditional effects. We can circumvent this difficulty, at least partially, by identifying the duration of the reinforcing stimulus with food-availability time, which can be operationally defined in terms of food-hopper onset and food-hopper offset. Typically, food-availability time in autoshaping is cued, either explicitly by the magazine light or less explicitly by the sound of the hopper hitting the magazine. Such cuing allows for a specification of the *P* system's parameters for the reinforcer.

A third limitation is that the arbitrary, noncued character of t as a unit of context-exposure time makes it theoretically irrelevant. Indeed, animals are not sensitive to temporal divisions that do not depend on stimulus onsets or offsets. However, we regard t not as a theoretically relevant variable but only as a variable that provides a useful basis for defining other variables that may or may not be theoretically relevant. Similarly, b and e can also be regarded only as useful bases for defining (in combination with t) theoretically more relevant variables, such as ISI, ITI, and $p(\text{US}|{\sim}\text{CS})$. Strictly speaking, then, the P system, in and by itself, is theoretically mute, because its defining variables are not intended to possess any theoretical value. The only purpose of the P system is to serve as a common parametric basis from which we can define different kinds of variables that may or may not be useful for experimental and theoretical work.

A fourth limitation relates to the beginning of the first and the end of the last t cycle of a session. Exactly at what point do these events occur? This question also arises in relation to one-trial procedures, which, from the perspective of the P system, can be regarded as one-t-cycle procedures. One possibility is to arrange conditions such that the experimental environment is dark before the beginning and after the end of a session (e.g., Grau & Rescorla, 1984). In terms of the P system, the houselight onset and offset would signal the beginning of the first t cycle and the end of the last t cycle of a session, respectively. But even this arrangement does not solve the problem completely, because nonvisual contextual cues also exist that are sensed by the animal before the houselight onset and after the houselight offset. This problem is especially acute in taste aversion and similar preparations, where training occurs in the animal's cage, thus making it difficult to specify the first and last t cycle.

Other Issues

In addition to the above limitations, we can identify other issues that do not represent intrinsic limitations of the P system but bear on its relevance for Pavlovian conditioning research. One issue arises from the distinction between effective and ineffective operations. We have shown that the P system is useful to organize procedures that involve both kinds of operations. For example, the system can be used to organize procedures involving manipulations of US duration. However, such manipulations are considered ineffective operations, since they do not produce significant effects on responding (e.g., Balsam & Payne, 1979; Runquist & Spence, 1959; Zeaman & Wegner, 1958; cf. Burkhardt & Ayres, 1978; Frey & Butler, 1973; Tait et al., 1983). Why, then, do we need a scheme that allows us to organize these kinds of procedures? Similar questions can be posed regarding other procedures that are usually considered ineffective, such as simultaneous and backward procedures.

Such questions can be answered by emphasizing that the main objective of the P system is to serve as a scheme for organizing, in a relatively comprehensive manner, Pavlovian procedures that are defined in terms of temporal and contingency variables. Including effective and ineffective operations represents a more comprehensive organizing strategy than does including only effective operations. Effectiveness is not a defining dimension of procedures, not even of relevant procedures, because one can regard ineffective procedures just as relevant for experimental research as effective ones. Indeed, the empirical content of a discipline is typically expressed in terms of comparisons between results obtained through effective procedures and results obtained through ineffective procedures.

Another issue relates to the (0,0) point of the S square. What does this point represent? This question raises doubts regarding the causal status of S_b and S_e, due to the fact that optimal circumstances depending on temporal parameters are represented in the S square by values very close to that point. The implication is that, as S_b and S_e approach zero, excitatory conditioning should be stronger, which leads to the conclusion that a simultaneous arrangement represents the maximally optimal circumstance for excitatory conditioning. This conclusion, however, seems to be inconsistent with the evidence, which raises a difficulty with S_b and S_e. This difficulty can be resolved by defining a different set of variables, such that the (0,0) point does not imply maximally optimal circumstances. Another possibility is to argue that simultaneous arrangements produce a response rather than a learning deficit—a hypothesis that has received some empirical support (e.g., Barnet, Grahame, & Miller, 1991, 1993; Matzel, Held, & Miller, 1988). On this basis, it can be argued that the (0,0) point of the S square produces maximum excitatory conditioning that is not expressed in performance.

Another difficulty relates to the kinds of invariances that arise from S_b and S_e. As we pointed out, any pair of values of S_b and S_e can be obtained from infinitely many combinations of values of t, b_{CS}, e_{CS}, b_{US}, and e_{US}. Take, for example, the pair (.025,0), which we associated with optimal circumstances for excitatory conditioning in NMR, autoshaping, and CER. The difficulty is that the very same pair of values can be obtained from values of t, b_{CS}, e_{CS}, b_{US}, and e_{US} that involve nonoptimal temporal parameters. Indeed, suppose, for example, that we applied to the NMR preparation the values of those variables estimated for CER. Such an application would involve an ISI of 15 sec, which is clearly nonoptimal for NMR. Three arguments are possible in this respect. First, S_b and S_e may not represent adequate ratios of temporal intervals—in which case, we would have to define and test other ratios. Second, an ISI of 15 sec may be optimal for NMR if combined with certain values of other temporal variables, such as TI, ITI, and interreinforcement interval. A similar argument can be made regarding other preparations, such as autoshaping (see Kaplan, 1985). Third, optimal circumstances may depend not only on temporal and contingency variables but also on stimulus intensity and modality. We can use the P system to test the first two arguments empirically. However, we cannot use it to determine whether or not stimulus intensity and modality constrain the effects of temporal and contingency optimal circumstances.

A fourth issue relates to the organization of more complex procedures, such as those used to produce conditioned inhibition, second-order conditioning, and blocking. These procedures are more complex in that they involve three stimulus classes—typically, two CSs (viz., CS_1 and CS_2) and one US. It is possible to derive these procedures from the *P* system by defining such classes, assigning values to *t*, *b*, and *e* for each class and defining conditional probabilities of occurrence of instances of each class. As an example, a typical conditioned-inhibition procedure involves "CS_1 & US" and "CS_1 & CS_2 & ~US" *t* cycles. Instances of these categories may occur at each *t* cycle (as determined *b* and *e*) so that a forward-delay procedure is in effect for "CS_1 & US" *t* cycles, and CS_1 and CS_2 occur concurrently in "CS_1 & CS_2" *t* cycles. Then, after assigning values to $p(CS_1)$ and $p(CS_2)$, we can stipulate that $p(US \mid CS_1) = 1$, and $p[\sim US \mid (CS_1 \; \& \; CS_2)] = 1$. Under such an arrangement, CS_2 is expected to become a conditioned inhibitor. A similar strategy can be adopted for second-order conditioning and blocking procedures.

Finally, there is the issue of the contributions of the *P* system to Pavlovian conditioning research. At present, it is premature to provide a definite conclusion in this respect. Experimental research is needed to determine the extent to which the system is useful for discovering ordered functional relations. For the purposes of the present paper, we regard the *P* system only as a scheme useful for organizing Pavlovian procedures. The applications we have described suggest that the *P* system may represent an improvement over other schemes, at least methodologically speaking. Indeed, the possibility of deriving different kinds of variables and procedures within a single parametric framework provides a kind of synthesis not found in other, more standard approaches, such as contiguity, contingency, and SET. These approaches have been far more selective regarding the kinds of variables considered as critical. This selectiveness has largely arisen from the assumption that Pavlovian conditioning theories must specify necessary and sufficient conditions that, so to speak, "energize" some kind of associative mechanism. The standard approaches thus differ in the ways they organize Pavlovian procedures, inasmuch as they differ in their proposed associative mechanisms.

The *P* system, in contrast, is methodologically oriented in that it is motivated by an attempt to organize Pavlovian procedures *in general*, without favoring any kind of variable as the critical determinant of conditioning or proposing any kind of underlying associative mechanism. The system thus permits an organization of different kinds of procedures that may be relevant for different theoretical propositions about associative mechanisms. But the *P* system may also facilitate theoretical synthesis through methodological synthesis. Methodological propositions such as the *P* system may thus be as relevant for the advancement of Pavlovian conditioning research as theoretical propositions.

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