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VARIETIES OF STIMULUS CONTROL IN MATCHING-TO-SAMPLE: A KERNEL ANALYSIS

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Conditional discrimination or matching-to-sample procedures have been used to study a wide range of complex psychological phenomena with infrahuman and human subjects. In most studies, the percentage of trials in which a subject selects the comparison stimulus that is related to the sample stimulus is used to index the control exerted by the relation between the stimuli. Performances indexed by percentage correct based on an aggregation across single trials, however, cannot identify the stimulus control topographies that exert momentary control of responding in a matching-to-sample milieu. The behavioral kernel is a unit of analysis that can provide such a measure. When a two-choice matching-to-sample procedure is used, analysis in terms of behavioral kernels permits the measurement of 16 potential stimulus control topographies. The kernel analysis provides the potential of assessing the many stimulus control topographies that control performances on a transient basis prior to the emergence of experimenter-specified conditional discriminative control. This sort of analysis could clarify the behavioral processes involved in the formation of learning set and problem-solving strategies when subjects are faced with complex discriminations, as well as the variables that influence these phenomena. As such, it is also related to accounts of discrimination learning as addressed by error-factor theory, hypothesis-based learning, and stimulus control topography coherence theory. Finally, a kernel analysis could also be used to diagnose specific sources of stimulus control that interfere with the formation of conditional discriminations by individuals with learning disabilities.

Key words: conditional discriminations, matching-to-sample, relational stimulus control, stimulus control topography, behavioral kernel

The matching-to-sample (MTS) procedure has been used to study a wide range of complex psychological phenomena. These include the establishment of relations of sameness (Cumming & Berryman, 1961, 1965; Carter & Werner, 1978; Mackay, 1991; Wright, Cook, Rivera, Sands, & Delius, 1988; Wright, Santiago, & Sands, 1984; Wright, Santiago, Urcioli, & Sands, 1983), difference

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(Pepperberg, 1988; Stromer & Stromer, 1990), and opposite (Dymond, Roche, Forsyth, Whalen, & Rhoden, 2008); arbitrary relations between meaningful terms or objects and referential symbols (Cerutti & Rumbaugh, 1993; Gisiner & Schusterman, 1992; Kennedy, Itkonen, & Lindquist, 1994; Lynch & Cuvo, 1995; Pepperberg, 1981; Schusterman & Gisiner, 1988); the formation of equivalence classes (Fields & Nevin, 1993; Schusterman & Kastak, 1993; Sidman, 1994); object permanence (Pepperberg, 1986); and the assessment of working memory (Santi & Roberts, 1985), among others.

In these studies, the control exerted by the relation between the stimuli was indexed by the percentage of trials that occasioned the selection of comparison stimuli that were related to a sample stimulus. When the trial-based percentage approximates 100% correct responding, one can reasonably conclude that the conditional relations have been established between sample and related comparison stimuli, and the phenomenon under study has been demonstrated.

When the trial-based percentages are below 100% accuracy or above 0% accuracy, however, the sources of stimulus control that are the determinants of responding are subject to a wide range of interpretations. One is that the conditional discrimination is only partially formed; another is that behavior is being controlled by some features or relations among the stimuli in the trials other than the conditional relation between the sample and positive comparison (Iversen, 1993, 1997; Iversen, Sidman, & Carrigan, 1986; McIlvane, Serna, Dube, & Stromer, 2000; McIlvane, Withstandley, & Stoddard, 1984; Sidman, 1992; Stromer & Osborne, 1982; Tomanari, Sidman, Rubio, & Dube, 2006). Each of these forms of stimulus control is referred to as a *stimulus control topography*, or STC (McIlvane & Dube, 1992). Thus, the underlying phenomenon cannot be evaluated because of the interfering effects of the other forms of stimulus control, or interfering STCs. A similar point was noted by Harlow (1949) in his presentation of error factor theory, which posited that errors were not mistakes but, rather, control of behavior by aspects of a stimulus array other than that defined by the experimenter.

Sidman (1978, 1980) illustrated the problem of interpreting trial-based percentage measures of accuracy by considering trials that contain one of two samples, A1 and A2, and two comparisons, B1 and B2, that can be presented on each side of the sample. A trial-based accuracy of 50% can be produced in a number of ways, three of which follow. First, 50% accuracy can be generated by the selection of comparison stimuli on a random basis. Second, 50% accuracy can be generated by the selection of the left-side comparison on all trials, regardless of the comparison stimulus in that position, which would indicate a position preference. Third, 50% accuracy can be generated by the selection of a given comparison on all trials, regardless of the comparison position of the sample stimulus, which would indicate a stimulus preference. Thus, the same trial-based percentage correct can be engendered by many different stimulus control topographies.

A similar argument was made for other trial-based percentage-correct measures. For example, 75% accuracy could be produced because the B1 comparison is selected in the presence of A1 on 75% of the trials and the B2 comparison is also selected in the presence of A2 on 75% of the trials. Thus, an overall trial-based accuracy might reflect similar levels of stimulus control exerted by the A1 and A2 samples. Alternatively, 75% accuracy would also be engendered by 100% selection of B1 given A1 and 50% accuracy in the selection of B2 given A2. Once again, the percentage of trials that occasion a given level of accuracy can reflect markedly different forms of stimulus control. In general, then, a trial-based percentage measure of accuracy that is substantially less than 100% and substantially greater than 0% accuracy does not provide a clear indication of the stimulus control topographies that are the determinants of behavior.

Sidman (1978, 1980) concluded that the sources of stimulus control in matching-to-sample trials can be determined only by a consideration of the comparisons that were selected on sets of trials that contained the same combination of samples and comparisons. Although it was promising, his matrix-based mode of analysis did not fully elaborate the range of stimulus control topographies that could influence performance by a given cluster of samples and comparisons, and was not designed to identify all of the relations among the stimuli in MTS trials that could control performances on a “moment to moment” basis.

The purpose of the present article is to refine the matrix analysis so that it can be used to identify all of the stimulus control topographies that can influence responding in a set of MTS trials. The approach is referred to as a *kernel analysis* (Buffington, Fields, & Adams, 1997; Fields, Landon-Jimenez, Buffington, & Adams, 1995). The development of the kernel analysis was also informed by the work of Levine (1966, 1975), who used the pattern of responding to probe stimuli to identify the relations among the stimuli in a complex cue that controlled responding on a previously presented training trial. A behavioral kernel is the minimal set of MTS trials needed to identify one instance of stimulus control. This occurs on an all-or-none, or quantal, basis for each kernel. For a two-choice MTS procedure, the kernel consists of a set of four trials, each of which has one of the configurations shown in Figure 1. Two of the stimuli are used as samples, A1 and A2. Each sample stimulus is presented in two trials. The same two comparison stimuli, B1 and B2, are presented on all four trials. For each sample, each comparison appears once on the left and once on the right.

A Behavioral Kernel

A1		A1		A2		A2	
B1	B2	B2	B1	B1	B2	B2	B1
+			+		+	+	

Figure 1. The four trials in a behavior kernel. Each trial contains one of two sample stimuli, listed on the top row, and two comparison stimuli, listed on the second row. The positions of the comparison stimuli are switched on each trial with the same sample. The row with +s indicates the correct comparison on each trial.

The second through fifth columns of Table 1 illustrate each of the four trials in a kernel. Because there are four trials in a kernel, there are 16 different patterns of responding that can be occasioned by the four trials in a kernel. Each pattern can be designated as a string of responses that involve the selection of the comparison presented on the left (L) or the right (R) for the trials in a row, and is listed in the first column of Table 1. For example, the first sequence, LRRL, indicates the selection of the comparison from the same set as the sample on all trials. The sequence on the last row is RRLR, and indicates the selection of B1 in the presence of the A2 sample and the selection of the right-hand comparison on both trials that contain the A1 sample.

Table 1
Stimulus Control Topographies Produced by a Behavioral Kernel

COMP SELECT	A1		A1		A2		A2		Percent Correct
	B1	B2	B2	B1	B1	B2	B2	B1	
LRRL	+			+		+	+		100
RLLR		--	--		--			--	0
LRLR	+			+	--			--	50
RLRL		--	--			+	+		50
RRRR		--		+		+		--	50
LLLL	+		--		--		+		50
LLRR	+		--			+		--	50
RRLL		--		+	--		+		50
LRLL	+			+	--		+		75
LRRR	+			+		+		--	75
LLRL	+		--			+	+		75
RRRL		--		+		+	+		75
RLLL		--	--		--		+		25
RLRR		--	--			+		--	25
LLLR	+		--		--			--	25
RLRR		--	--			+		--	25

Note. Sixteen patterns of responding that can occur in the presence of the four trials that constitute a behavioral kernel. The four configurations are presented at the top of columns 2 through 5. The +s and –s on a row indicate the comparisons selected, where + indicates a selection that is set consistent and is correct, whereas – indicates a selection that is not set consistent and is incorrect. Trial-based percentages correct are listed in each row for the corresponding pattern of comparison selections. The COMP SELECT column indicates the left- and right-hand comparisons that are selected for the four configurations.

The sequence of comparison selections is keyed to the trial configurations at the top of the columns in Table 1. Although the four trial configurations can be presented in different orders, the comparison selected for a particular trial configuration would be the same, regardless of actual order of presentation of the different configurations. Thus, each sequence represents a unique pattern of comparison selections, regardless of the order in which the four trials are presented.

Each of the 16 patterns of comparison selection across the four trials in a kernel can reflect a unique form of stimulus control that governs responding on the trials in that kernel. Each pattern and its possible stimulus control topography (McIlvane & Dube, 1992) will be described next. Finally, the last column in Table 1 indicates the trial-based percentage correct that would be generated by the set of comparison selections in that row. One string occasions 100% selection of positive comparisons. Six strings occasion 50% accuracy. Four strings occasion 75% accuracy, and the remaining four strings occasion 25% accuracy. Finally, one string occasions 0% selection of positive comparisons.

Conditional Control

The first two sequences designate conditional control of comparison selection. They are referred to as 100% and Zero.

"100%" represents 100% accuracy across the trials in the kernel. This pattern of responding indicates selection of comparison stimuli that belong to the same set as the prevailing sample on all trials. B1 is selected in the presence of A1, and B2 is selected in the presence of A2. These performances indicate the existence of conditional discriminative control defined by the experimenter.

This analysis makes the assumption that the 100% pattern does not represent an instance of a reject relation in which the selection of the positive comparison represents responding away from the negative comparison or behavior controlled by a reject relation (Fucini, 1982; Johnson & Sidman, 1993). The validity of this assumption has been supported by the results of recently published research showing that reject relations are typically not formed in two-choice MTS trials (Saunders, Chaney, & Marquis, 2005). These results, then, support the notion that the 100% SCT reflects one instance of a select relation and, by implication, the Zero SCT reflects an instance of one reject relation.

"Zero" represents 0% accuracy of comparison selection on all of the trials in a kernel. This level of accuracy indicates selection of comparison stimuli that belong to the set opposite to that of the prevailing sample. B1 is selected in the presence of A2, and B2 is selected in the presence of A1. Although performance indicates conditional discriminative control, it is opposite to that specified by the experimenter. As with the 100% outcome, this analysis makes the assumption that the Zero outcome does not represent an instance of a reject relation in which the selection of the negative comparison represents responding away from the positive comparison.

Preferences for Stimuli or Position, and Sample-Based Discriminations

Six patterns of comparison selection occasion 50% accuracy. They indicate different sources of stimulus control and are referred to as "Co1P" and "Co2P," "Left" and "Rite," and "S1-L" and "S1-R."

Co1P indicates the selection of the B1 comparison stimulus, regardless of its location. It is likely that the B1 comparison that is being tracked is functioning as an Sd. The subject is probably not attending to the sample stimuli. In addition, all of the remaining stimuli presented in the experiment are functioning as S^s.

Co2P indicates the selection of the B2 comparison stimulus, regardless of its location. It is likely that the B2 comparison that is being tracked is functioning as an Sd. The subject is probably not attending to the sample stimuli. In addition, all of the remaining stimuli presented in the experiment are functioning as S^s.

Treated separately, each SCT reflects an idiosyncratic bias for one comparison relative to the other. Treated together, they represent an aggregate measure of discriminative control by comparison stimuli without regard to the prevailing sample stimuli.

“Left” is a 50% performance generated by the selection of the comparison key on the left side of a stimulus display. This occurs regardless of the sample presented on the trial or the stimuli presented on the left-hand comparison key on a given trial. The illumination of the samples and comparisons functions as an Sd for pressing the left key. Behavior is not controlled by the particular stimuli presented as samples and comparisons. The absence of the sample and comparison stimuli functions as an S^ for pressing the left key. Thus, left-key responding is behavior that is under the control of a presence–absence discrimination. This sort of performance has also been referred to as a *position preference*. Although commonly used, that terminology is an incomplete specification of the discriminative stimuli of which the response is a function, since the pressing of the left comparison key does not occur in the absence of illuminated sample and comparison panels.

“Rite” is a 50% performance generated by the selection of the comparison key on the right side of the intelligence panel. This occurs regardless of the sample presented on the trial and the comparison that is present on the right-hand key. The illumination of the samples and comparisons functions as an Sd for pressing the right key. Behavior is not controlled by the particular stimuli presented as samples or comparisons. The absence of the sample and comparison stimuli functions as an S^ for pressing the right key. Thus, responding on the right-hand comparison key is behavior that is under the control of a presence–absence discrimination. Although this has also been called a *position preference*, that phrase does not specify discriminanda of which the response is a function.

Treated separately, these SCTs reflect idiosyncratic discriminative control exerted by the location of the comparison keys relative to the each other. Treated together, they represent an aggregate measure of discriminative control by position, without regard to the prevailing sample or comparison stimuli.

S1-L is a 50% performance generated by the selection of the left comparison key in the presence of the Set 1 sample (A1), and the selection of the right comparison in the presence of the Set 2 sample (A2). These selections occur regardless of the comparison stimuli that are present on a given trial. The presentation of the comparison stimuli acts as a cue for responding but does not control the topography of the response. Behavior, then, is under the discriminative control of the sample stimuli presented on the trials in the kernel.

S1-R is a 50% performance generated by the selection of the right comparison key in the presence of the Set 1 sample (A1), and the selection of the left comparison in the presence of the Set 2 sample (A2). These selections occur regardless of the comparison stimuli that are present on a given trial. As with the S1-L, the presentation of the comparison stimuli acts as a cue for responding but does not control the topography of the response. Rather, behavior is under the discriminative control of the sample stimuli presented on the trials in the kernel.

To summarize, 50% accuracy could reflect (a) preference for a comparison stimulus regardless of the sample or the position of comparison presentations; (b) positional preference under the control of a presence–absence discrimination; (c) differential responding to position, which is under the simple discriminative control of the sample stimuli, regardless of the comparisons; or (d) random responding that does not reflect any of the former stimulus control topographies.

Treated separately, these SCTs reflect idiosyncratic discriminative control exerted by the sample stimuli relative to each other. Treated together, they represent an aggregate measure of discriminative control by sample stimuli without regard to the prevailing comparison stimuli.

Conditional and Simple Discriminative Control

Four patterns of comparison selection occasion 75% accuracy. They indicate different forms of stimulus control by each sample stimulus. The different sources are referred to as "+1LL," "+1RR," "+2LL," and "+2RR."

+1LL is a 75% performance generated by the selection of the experimenter-defined correct comparison on three of the four trials in a kernel. In the presence of the A1 sample, subjects select the correct comparison regardless of its position. In addition, the subject selects the left-hand comparison on both trials that contain the A2 sample. This performance indicates conditional control of responding by the A1 sample and discriminative control of positional responding by the A2 sample.

+1RR is a 75% performance generated by the selection of the experimenter-defined correct comparison on three of the four trials in a kernel. In the presence of the A1 sample, subjects select the correct comparison regardless of its position. In addition, the subject selects the right-hand comparison on both trials that contain the A2 sample. This performance indicates conditional control of responding by the A1 sample and discriminative control of positional responding by the A2 sample.

+2LL is a 75% performance generated by the selection of the experimenter-defined correct comparison on three of the four trials in a kernel. In the presence of the A2 sample, subjects select the correct comparison regardless of its position. In addition, the subject selects the left-hand comparison on both trials that contain the A1 sample. This performance indicates conditional control of responding by the A2 sample and discriminative control of positional responding by the A1 sample.

+1RR is a 75% performance generated by the selection of the experimenter-defined correct comparison on three of the four trials in a kernel. In the presence of the A2 sample, subjects select the correct comparison regardless of its position. In addition, the subject selects the right-hand comparison on both trials that contain the A1 sample. This performance indicates conditional control of responding by the A2 sample and discriminative control of positional responding by the A1 sample.

These SCTs can be combined in different ways. When the +1s and +2s are treated together, they represent an aggregate measure of conditional responding by one sample stimulus that exerts experimenter-defined conditional control without regard to the class membership of the sample, and without regard to the positional responding controlled by the other sample.

When the LLs and RRs are treated together without regard to the +1 and +2 designations, they represent an aggregate measure of discriminative control of positional responding by one sample stimulus without regard to the class membership of the sample, and without regard to the conditional responding controlled by the other sample.

Inverse Conditional and Simple Discriminative Control

The last four patterns of comparison selection occasion 25% accuracy. These patterns indicate inverse conditional control and simple discriminative control by each of the sample stimuli. They are referred to as "-1LL," "-1RR," "-2LL," and "-2RR."

-1LL is a 25% performance generated by the selection of the experimenter-defined negative comparison on three of the four trials in a kernel. In the presence of the A1 sample, subjects select the negative comparison regardless of its position. In addition, the subject selects the left-hand comparison on both trials that contain the A2 sample. This performance indicates inverse conditional control of responding by the A1 sample and discriminative control of positional responding by the A2 sample.

-1RR is a 25% performance generated by the selection of the experimenter-defined negative comparison on three of the four trials in a kernel. In the presence of the A1 sample, subjects select the negative comparison regardless of its position. In addition, the subject selects the right-hand comparison on both trials that contain the A2 sample. This performance indicates inverse conditional control of responding by the A1 sample and discriminative control of positional responding by the A2 sample.

-2LL is a 25% performance generated by the selection of the experimenter-defined negative comparison on three of the four trials in a kernel. In the presence of the A2 sample, subjects select the negative comparison regardless of its position. In addition, the subject selects the left-hand comparison on both trials that contain the A1 sample. This performance indicates inverse conditional control of responding by the A2 sample and discriminative control of positional responding by the A1 sample.

-2RR is a 25% performance generated by the selection of the experimenter-defined negative comparison on three of the four trials in a kernel. In the presence of the A2 sample, subjects select the negative comparison regardless of its position. In addition, the subject selects the right-hand comparison on both trials that contain the A1 sample. This performance indicates inverse conditional control of responding by the A2 sample and discriminative control of positional responding by the A1 sample.

These sequences can be combined in different ways. When the -1s and -2s are treated together without regard to the LL and RR designations, they represent an aggregate measure of conditional responding by one sample stimulus that exerts conditional control that is opposite to the experimenter-defined contingencies without regard to the class membership of the sample, and without regard to the positional responding controlled by the other sample. When the LLs and RRs are treated together without regard to the -1 and -2 designations, they represent an aggregate measure of discriminative control of positional responding by one sample stimulus without regard to the class membership of the sample, and without regard to the conditional responding controlled by the other sample.

Cross-Sectional and Longitudinal Kernel Analyses

The acquisition of conditional discriminations can be observed in one of two ways with a kernel analysis: cross-sectionally or longitudinally. A cross-sectional kernel analysis involves the aggregation of all data during some temporal epoch, such as acquisition, and the measurement of the relative frequencies of each SCT during that epoch. This provides a temporal snapshot of the prevalence of the different SCTs during the entire epoch. On the negative side, it removes from the analysis the serialized changes in stimulus control topographies that can, and most likely do, occur during the epoch.

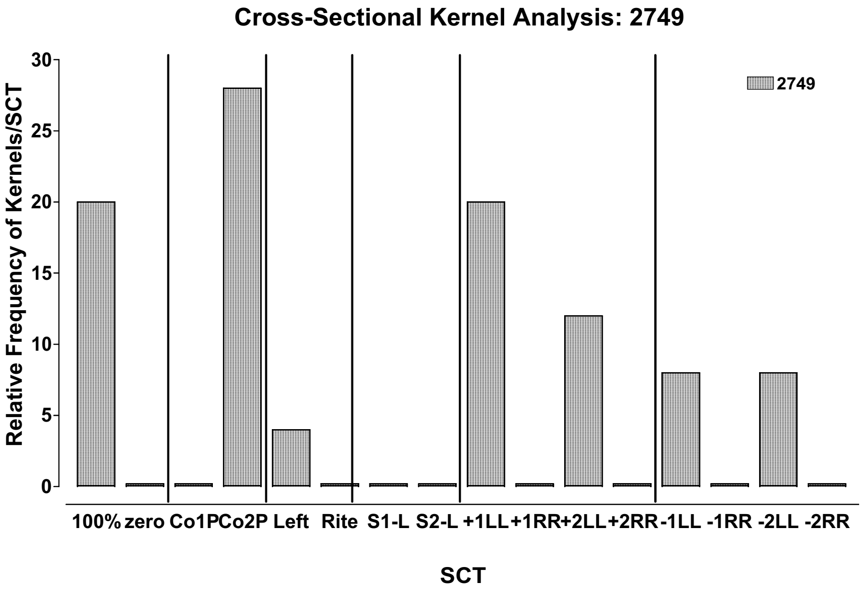
In contrast, a longitudinal kernel analysis plots changes in SCTs across the kernels as they are presented. This provides information about the emergence and submergence of SCTs from the start of training until all kernels occasion the experimenter-defined conditional control of responding. If there is a great deal of kernel-to-kernel variation, however, it is difficult to discern differences in the occurrence of particular stimulus control topographies during the epoch. That is best accomplished with the above-mentioned cross-sectional kernel analysis. Thus, the combination of cross-sectional and longitudinal kernel analysis should provide a relatively comprehensive characterization of the stimulus control topographies that exert transient control of responding during the formation of conditional discriminations.

The results of cross-sectional kernel analyses and longitudinal kernel analyses will be illustrated in the remainder of the article via reference to some empirical data collected during the concurrent training of five arbitrary conditional discriminations—AB, BC, CD, DE, and EF—which were the precursors of two four-node, six-member equivalence classes.

Cross-Sectional Kernel Analysis for Single Subjects: SCT Effects

When a cross-sectional kernel analysis is conducted, it is necessary to consider whether the relative frequencies of the SCTs reflect random responding. If responding was random, each of the 16 STCs would occur with the same relative frequency—in this case, 0.063, or 1 in 16. Statistically significant deviations from a platykurtic distribution would indicate that the performances were influenced by 1 of the 16 SCTs and would not reflect random responding. These options can be evaluated by conducting a chi-square trend analysis. Significance would imply performances controlled by SCTs.

Each panel in Figure 2 shows the relative frequencies of each SCT during the acquisition of the above-mentioned conditional discriminations for two participants. The upper panel presents the data for Subject 2749. The kernels that produced the “100%” SCTs emerged from the start of training until the first kernel in the run of consecutive kernels that defined the formation of each of the conditional discriminations. A chi-square trend analysis proved to be significant, $\chi^2 = 18.27$, $df = 1$, $p < .0001$, which indicated that the differential prevalences seen in Figure 2 reflected control of responding by different SCTs during the course of acquisition.



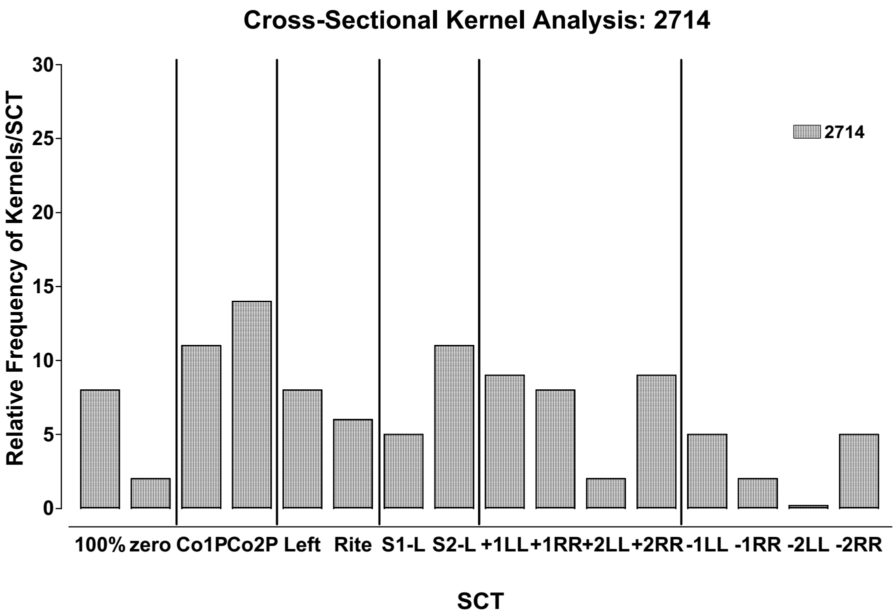


Figure 2. Cross-sectional kernel analysis for Subjects 2749 and 2714. Data for each subject are presented in separate panels. Each panel presents the relative frequency of occurrence of stimulus control topographies (SCTs) arrayed on the abscissa. Consult text for the meaning of each SCT.

The stimulus control topographies that showed conditional discriminative control, 100% and Zero together, occurred with relatively high frequencies.

These two stimulus control topographies, however, did not occur with equal frequencies. Rather, all of the conditional discriminative responding was in accordance with the experimenter-defined contingencies.

Kernels that occasioned comparison preferences, Co1P and Co2P, occurred most frequently. For this subject, the preference was for the comparisons in Class 2 only. This is a source of stimulus control that has not been previously documented during the formation of conditional discriminations. This finding raised the following questions: To what extent does a comparison preference influence the formation of arbitrary conditional discriminations? Would the elimination of pre-experimental preferences for particular comparisons influence the subsequent establishment of arbitrary conditional discriminations?

Other kernels occasioned positional preferences. These kernels, labeled **"Left"** and **"Rite,"** did not occur with equal frequencies. Finally, fewer kernels showed positional responding than comparison preferences or conditional discriminative control. When positional responding occurred, it always involved responding on the left key. The subject never showed discriminative control of positional responding by the sample stimuli alone. This finding raises questions like those mentioned in the preceding paragraph. To what extent does a position preference influence the formation of arbitrary conditional discriminations? Would the elimination of this pre-experimental preference for location-based control of responding influence the subsequent establishment of arbitrary conditional discriminations?

The next section in the upper panel of Figure 2 shows the frequency of kernels that occasioned experimenter-defined conditional discriminative control by one sample and simple discriminative control by the other sample. The first and third bars show that conditional control was exerted more frequently by the Class 1 sample than the Class 2 sample. In addition, the other samples exerted discriminative control of positional responding to the left only. This finding is consistent with those kernels that showed positional preferences only. Those kernels occasioned responding to the left key only.

The last section in the upper panel of Figure 2 shows the frequency of kernels that occasioned conditional discriminative control that was opposite to the experimenter-defined contingencies by one sample, and simple discriminative control by the other sample. First, these complex SCTs occurred with lower frequencies than did the SCTs that showed complex control where one sample occasioned experimenter-defined conditional discriminative control. Otherwise, the prevalences were like those described in the prior section. Specifically, one of the samples in each kernel exerted discriminative control of left-key responding.

The lower panel in Figure 2 presents data for Participant 2714. A chi-square trend analysis showed a high level of significance, $\chi^2(16,1) = 12.78$, $p < 0.0001$. Therefore, the relative frequencies of the different SCTs could not be accounted for by random responding.

The stimulus control topographies that showed conditional discriminative control, **100%** and **Zero**, occurred with relatively low frequencies. Although most of the conditional discriminative responding was in accordance with the experimenter-defined contingencies, some kernels occasioned conditional control that was opposite to that stipulated by the contingencies.

Kernels that occasioned comparison preferences, Co1P and Co2P, occurred more frequently than the other SCTs. This subject shows similar momentary preferences for both of the comparisons. The kernels that occasioned positional preferences occurred with similar frequencies. Finally, fewer kernels showed positional responding than comparison preferences or conditional discriminative control.

Many kernels showed discriminative control of positional responding by sample stimuli alone. The subject was twice as likely to show discriminative control of left-key responding by the Class 2 sample and right-key responding by the Class 1 sample, instead of the opposite. This sort of discriminative control of positional responding was not seen with Subject 2749.

The next section in the lower panel of Figure 2 shows the frequency of kernels that occasioned experimenter-defined conditional discriminative control by one sample and simple discriminative control by the other sample. Three of the four stimulus control topographies occurred with essentially equal likelihood: **+1LL**, **+1RR**, and **+2RR**.

The last section in the lower panel of Figure 2 shows the frequency of kernels that occasioned conditional discriminative control that was opposite to the experimenter-defined contingencies by one sample and simple discriminative control by the other sample. When taken together, these four complex SCTs occurred with a lower aggregate frequency than did the SCTs that showed complex control where one sample occasioned experimenter-defined conditional discriminative control.

Cross-sectional kernel analysis and individual differences. The two panels in Figure 2 also permit a comparison of performances occasioned by corresponding SCTs for each subject. In many cases, the same SCT occurred with different relative frequencies across subjects. For example, preferences for the Class 2 comparison were much more likely to occur for Subject 2749 than for Subject 2714. In other cases, the frequencies of pairs of related SCTs occurred with similar patterns across subjects. For example, kernels were more likely to evoke experimenter-defined conditional discriminative control than conditional control that was opposite to the experimenter-defined contingencies, that is, **100%** SCT >> **Zero** SCT. In contrast to this commonality, transient discriminative control of positional responding by the sample stimuli was shown by one subject and did not occur at all for the other subject. To what extent is this difference correlated with speed of acquiring conditional discriminations or the formation of equivalence classes? When positional responding was observed, both subjects showed a somewhat greater likelihood of responding to the left key than the right. This might suggest a revision of the experimental apparatus to eliminate such a positional bias.

The phrase “individual differences in learning style” typically denotes the acquisition of discriminations or conditional discriminations by attending to stimuli in one sensory modality rather than another. Thus, a cross-sectional kernel analysis provides an alternative way of operationalizing individual differences in learning. Specifically, individual differences could be quantified in terms of differential prevalences of SCTs that influence performances on a transient basis during the course of acquiring conditional discriminations.

Cross-Sectional Kernel Analysis of One SCT: Tracking the Effect of Nodal Distance

In addition to the previous example, a cross-sectional kernel analysis has been used to document the effects of nodal distance on the delayed emergence of the experimenter-defined conditional discriminative control of behavior, denoted in the current context as the **100%** SCT (Buffington et al., 1997; Fields et al., 1995). These experiments involved the establishment of three-node, five-member equivalence classes that were established by training the baseline conditional discriminations AB, BC, CD, and DE. Thereafter, subjects were presented with zero-, one-, two-, and three-node emergent relations probes. Aggregated across testing blocks and plotted as a function of the nodal number, the percentage of kernels that evoked relational responding was an inverse function of nodal distance for two types of participants: subjects who showed the delayed emergence of equivalence classes and subjects who failed to form equivalence classes.

Longitudinal Kernel Analysis

As mentioned above, a longitudinal kernel analysis can be used to document the STCs that emerge serially during the entire process of acquisition. As in the cross-sectional analysis, however, the issue of randomness must also be addressed to minimize the likelihood of concluding that an STC was a determinant of responding when the responses to the trials in a kernel could have been occurring at random.

The most liberal approach would be to conclude that the pattern of responding produced by each kernel represents an SCT that is a momentary determinant of performance. The problem with drawing such a conclusion is that it is equally plausible to assume that the sequence of four responses reflects random selection of comparisons and not control of behavior by antecedent stimuli. In contrast, if many consecutively presented kernels occasion the same pattern of responding to the four trials in each kernel, it is likely that a given stimulus control topography was the determinant of performances during those kernels. Furthermore, the certainty about control of behavior by a particular stimulus control topography would grow substantially with the number of consecutive kernels that occasioned the same response pattern.

What, then, is the minimum number of consecutive kernels needed to demonstrate stimulus control of responding? Each of the four trials in a kernel occasions a particular comparison selection. In addition, when the kernel is repeated, the same comparison selections are occasioned by trials of the same configuration, even though the order of presenting the configurations will differ. The chance probability that a particular pattern of responding will occur across the eight trials of the two consecutive kernels is less than 0.004, or 1 in 256. Therefore, it is plausible to conclude that behavior is controlled by a given constellation of stimuli when the same pattern of responding is occasioned by at least two consecutive kernels.

Tabular Representation of Longitudinal Kernel Analysis

Table 2 illustrates a longitudinal kernel analysis of data obtained from Subject 2749 that had been used in the cross-sectional kernel analysis. As mentioned earlier, data were obtained during the concurrent training of AB, BC, CD, DE, and EF conditional discriminations. The rightmost columns depict data for given conditional discriminations. Each row represents data obtained from one block of 20 trials, or one kernel for each of the five conditional discriminations. The entries in each cell list the SCT occasioned for that block and particular conditional discrimination.

Table 2
Stimulus Control Topographies (SCTs) for Kernels

Block	AB	BC	CD	DE	EF
1	**100%**	**Co2P**	**100%**	**-1RR**	**Left**
2	**+1LL**	**S2-L**	**-2LL**	**100%**	**+1LL**
3	**+1LL**	**S2-L**	**S2-L**	**+2LL**	**Co2P**
4	**100%**	**+1LL**	**Co2P**	**Co2P**	**Co2P**
5	**100%**	**100%**	**100%**	**+2RR**	**Co2P**
6	**+1LL**	**100%**	**100%**	**100%**	**+2LL**
7	**100%**	**100%**	**100%**	**100%**	**100%**

Note. The stimulus control topographies (SCTs) occasioned by AB, BC, CD, DE, and EF kernels in each training block for Subject 2749. See text for the meaning of each SCT.

Acquisition occurred relatively quickly, in seven blocks, to be specific. Using the two-consecutive-kernel rule, the AB kernel in Blocks 2 and 3 occasioned conditional control by one sample and positional control by the other. This was followed by the emergence of experimenter-defined conditional control in Block 4. When the BC kernels are examined, the BC kernels in Blocks 2 and 3 occasioned discriminative control of positional responding by the sample stimuli. This was followed by the emergence of experimenter-defined conditional control in Block 5. When the EF kernels are examined, the EF kernels in Blocks 3, 4, and 5 occasioned discriminative control by the Class 2 comparison stimulus. This was followed by the emergence of experimenter-defined conditional control in Block 7.

Graphic Representation of a Longitudinal Kernel Analysis

Table 2 listed the SCTs that controlled responding on a serial basis during the establishment of five conditional discriminations. It is also possible to present the results of a longitudinal kernel analysis in a graphical manner by the use of a 16-channel strip chart. The abscissa lists the succession of kernels presented in a training session. Each line on the strip chart registers one of the 16 SCTs that can influence performance, as described above. For each kernel, a data point is placed on the line that corresponds to the response pattern observed for that kernel. If a given pattern of responding is evoked on at least two consecutive kernels, that would indicate that a given SCT was the determinant of responding for those kernels and is highlighted by circling them. Figures 3, 4, 5, and 6 provide a few examples of this form and data presentation. They were selected to illustrate the variety of outcomes that can be disclosed from such an analysis.

The strip chart in Figure 3 contains data for the AB kernel for Subject 2746. During Kernels 4 and 5, the Class 1 sample exerted conditional control and the Class 2 sample exerted discriminative control of positional responding. Control of responding then shifted to a preference for the Class 2 comparison during Kernels 6 and 7. Kernels 9 and 10 showed inverse conditional control, followed by experimenter-defined conditional discriminative control in Kernel 11, which was maintained to the end of the session.

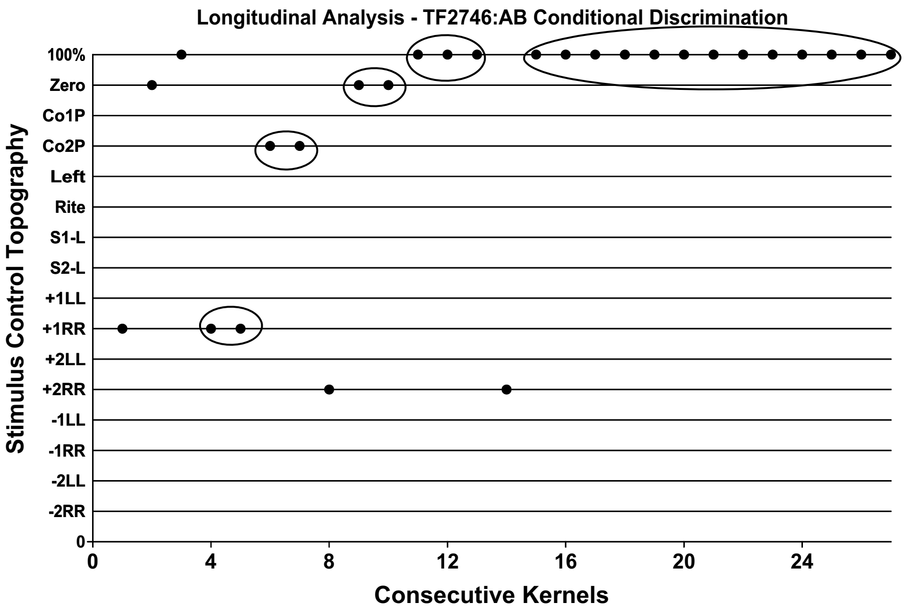


Figure 3. Longitudinal kernel analysis for the AB conditional discrimination for Subject 2746. The occurrence of each stimulus control topography (SCT) is plotted as a function of the successive presentation of the AB kernels during the acquisition of the conditional discrimination. A dot on a line of the strip chart indicates the occurrence of the particular SCT on the kernel presentation indicated by a perpendicular dropped from the data point to the abscissa. Consult text for the meaning of each SCT. The ovals encircle at least two consecutive kernels that occasion the same SCT.

The strip chart in Figure 4 contains data for the DE kernel for Subject 2708. During Kernels 2 and 3, the Class 1 sample exerted inverse conditional control and the Class 2 sample exerted discriminative control of positional responding. Positional responding then came under the discriminative control of the sample stimuli in Kernels 6 and 7. Kernels 9 and 10 showed behavior controlled by a positional preference. The shifting response pattern occasioned by the five subsequent kernels (11–15) suggested that subjects were responding at random for an extended period of time. Finally, in Kernel 16, behavior came under the experimenter-defined conditional discriminative control, which was maintained to the end of the session. The strip charts in Figures 3 and 4, then, showed that transient control of responding can be exerted by many different stimulus control topographies—six in these examples.

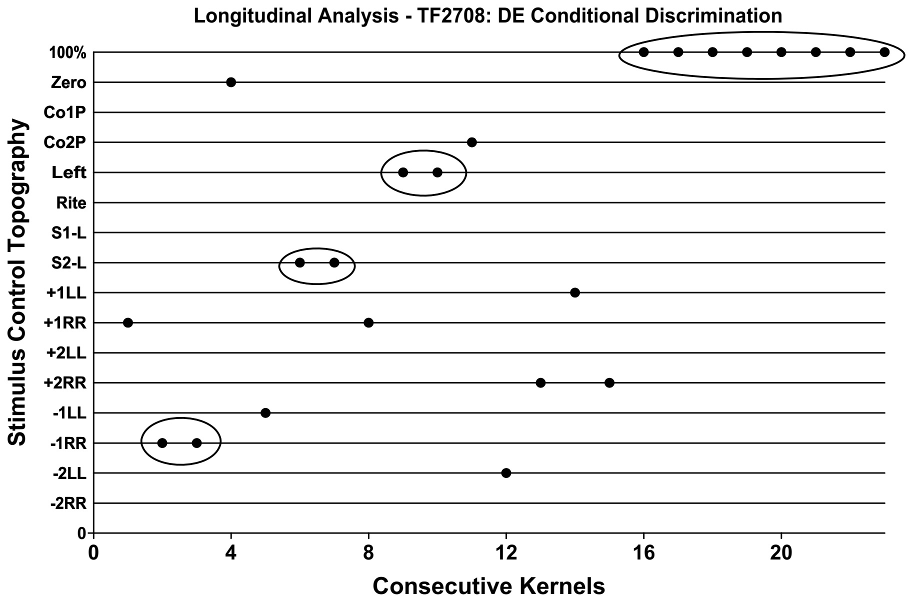


Figure 4. Longitudinal kernel analysis for the DE conditional discrimination for Subject 2708. The occurrence of each stimulus control topography (SCT) is plotted as a function of the successive presentation of the succession of AB kernels during the acquisition of the conditional discrimination. A dot on a line of the strip chart indicates the occurrence of the particular SCT on the kernel presentation, which is identified by the perpendicular dropped from the data point to the abscissa. Consult text for the meaning of each SCT. The ovals encircle at least two consecutive kernels that occasion the same SCT.

The strip chart in Figure 5 contains data for the DE kernel for Subject 2746, and these data are included to illustrate extended transient control of behavior during conditional discrimination learning. In Kernels 3 and 4, the Class 2 sample exerted experimenter-defined conditional control and the Class 1 sample exerted discriminative control of positional responding. Control of responding then shifted to a preference for the Class 2 comparison stimulus, which was maintained for seven of eight consecutive kernels (5—12). These data stand in contrast to the performances illustrated in Figures 3 and 4, where transient control was exerted by a given SCT for the minimum of two consecutive kernels. Finally, in Kernel 15, behavior control shifted abruptly to conditional discriminative control stipulated by the experimenter and was maintained to the end of the session.

Control of behavior by experimenter-defined conditional discriminations. A longitudinal kernel analysis can also be used to document the acquisition of conditional discriminations by plotting the relative frequency of kernels that evoke only one SCT, for example, the experimenter-defined conditional discriminations over successive training blocks. This sort of analysis is shown for Subject 2746 in Figure 6. Each training block contained the trials needed to measure one AB, BC, CD, DE, and EF kernel. The block was repeated until all kernels occasioned the 100% SCT. Acquisition was tracked by measuring the percentage of AB, BC, CD, DE, and EF kernels in each block that occasioned the pattern of responding indicative of the 100% SCT.

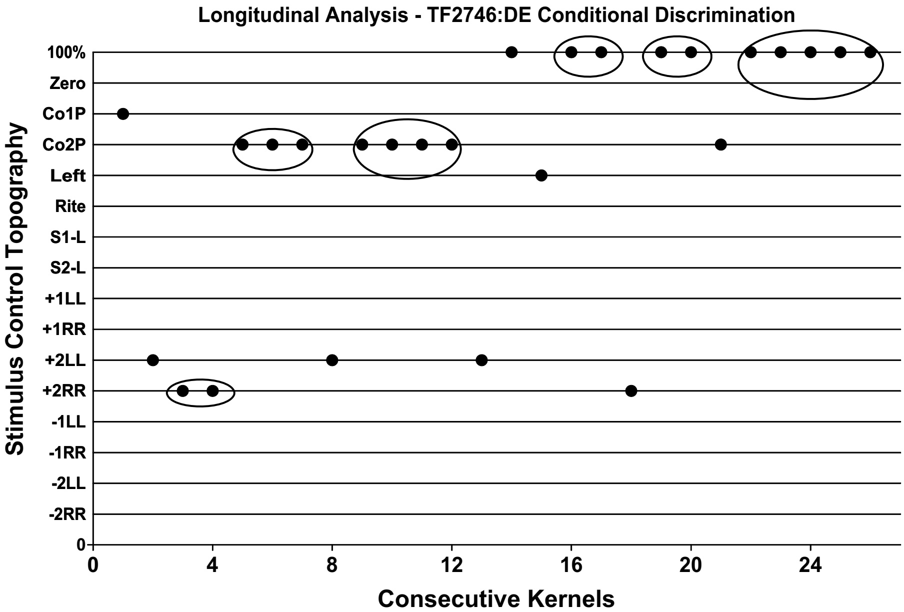


Figure 5. Longitudinal kernel analysis for the DE conditional discrimination for Subject 2746. The occurrence of each stimulus control topography (SCT) is plotted as a function of the successive presentation of the AB kernels during the acquisition of the conditional discrimination. A dot on a line of the strip chart indicates the occurrence of the particular SCT on the kernel presentation indicated by a perpendicular dropped from the data point to the abscissa. Consult text for the meaning of each SCT. The ovals encircle at least two consecutive kernels that occasion the same SCT.

In the first 10 blocks (see section A) most of the kernels did not evoke relational responding. This was followed by a systematic increase in the percentage of kernels that evoked relational responding, which stabilized by oscillating between 40% and 60% for many blocks (see the latter kernels in Section B and all of Section C). Thereafter, the percentage of kernels that evoked relational responding increased rapidly (Section D) and became asymptotic where all kernels evoked relational responding (Section E), which documented the acquisition of the conditional discriminations.

Figure 6 also depicts acquisition using the percentage of trials that evoke correct responding. Subjects responded at about 60% accuracy in the trials presented in Sections A and B. Although this value did not change, there was a systematic increase in the percentage of kernels that evoked relational responding. The trial-based percentage-correct measure, then, did not disclose the formation of relational responding during those trials. In Section D, the trial-based percentage-correct measure showed a systematic increase in response accuracy. In contrast, there was no change in the percentage of kernels that evoked relational responding in the same set of trials. In this case, trial-based accuracy overestimated the acquisition of relational responding by the subject. In that segment, the kernel analysis showed a lagging and rapid increase in the evocation of relational responding. Additional research will be needed to assess the validity of each as an indicator of conditional discrimination learning.

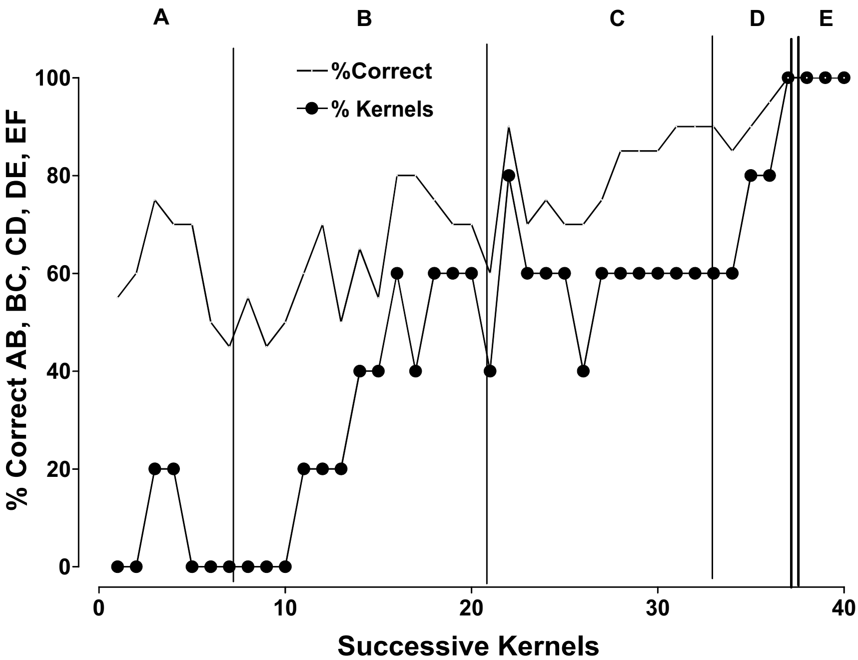


Figure 6. The percentage of 100% SCTs that occur in successive kernels during the concurrent training of five conditional discriminations and the percentage of correct trials that occur during those same five conditional discriminations, both of which are plotted as a function of successive kernels during acquisition. The sections labeled A through E are referred to in the text.

Discussion

The behavioral kernel is the minimal unit of analysis that can be used to document single instances of stimulus control in a matching-to-sample setting. The forms of stimulus control that can be documented by a kernel include (a) preferences for position or comparison stimuli, (b) simple discriminations of positional responding by sample stimuli, (c) experimenter-defined conditional control, (d) conditional control that is opposite to that defined by experimental contingencies, and (e) conditional selection by one sample and simple discriminative control by the other. A cross-sectional kernel analysis characterizes the prevalence of various SCTs that emerge during an epoch of training trials. A longitudinal kernel analysis characterizes the momentary shifts in SCTs that exert transient control of responding during the formation of conditional discriminations. A number of examples were used to illustrate both sorts of analysis with data collected during the concurrent training of a number of arbitrary conditional discriminations.

Kernel analysis and other behavioral phenomena. The two forms of kernel analysis could be used to explore other behavioral processes, such as the delayed or gradual emergence of derived relations during the formation of equivalence classes (Bentall, Dickins, & Fox, 1993; Devany, Hayes, & Nelson, 1986; Dickins, Bentall, & Smith, 1993; Fields, Adams, Verhave, & Newman, 1990; Holth & Arntzen, 1998; Imam, 2001; Kennedy, 1991; Sidman, 1994; Spradlin, Cotter, & Baxley, 1973), and the development of learning set (Harlow, 1949; Mackintosh, 1974; Miles, 1965; Murray & Gaffan, 2006; Perez-Gonzalez, Spradlin, & Saunders, 2006; Saunders & Spradlin, 1993; Slotnick & Hodos, 2000; Warren, 1965). In addition, the behavioral kernel could be used as an independent variable that might influence the formation of arbitrary conditional discriminations.

Delayed emergence of derived relations occurs when probes do not initially evoke class-consistent relational responding. With trial repetition, however, responding comes to be determined by a stimulus control topography that is indicative of relational control by class membership. Before that, however, other aspects of the probe stimuli may be controlling behavior. Cross-sectional and longitudinal kernel analyses would allow for the identification of those stimulus control topographies and the tracking of changes during the process of delayed emergence.

Learning set has been demonstrated when an individual acquires new sets of unrelated discriminations in fewer and fewer trials. Each set contains a number of simultaneous discrimination problems that are unrelated to each other, for example, AB, CD, EF, and so forth, and are also unrelated to the discrimination problems presented in subsequent stimulus sets (e.g., GH, IJ, KL). Although there is a substantial decrease in the number of trials needed to learn the discriminations in the successive sets, it cannot reach zero because the stimuli across sets are unrelated to each other. Although it is impossible to respond correctly to the stimuli in any new set on first exposure, after learning many problem sets, all trials can evoke correct responding on the second training block in a set. Indeed, the percentage of correctly solved problems on the second training block for a set has been taken as the quintessential measure of learning set. Specifically, perfect discriminative performances evoked by the trials presented on the second training block have been attributed to the participants' acquired ability to attend to features of stimuli that are correlated with the stimuli presented, the responses evoked, and the reinforcement or nonreinforcement occasioned during the trials in Training Block 1. When this occurs, subjects have learned to learn. Although many more learning set studies has been conducted in the context of simultaneous discriminations, some have been conducted during the establishment of sets of arbitrary conditional discriminations. Although similar outcomes have been reported, none of them have documented fine-grained shifts in the stimulus control topographies that influenced responding during the acquisition of the conditional discriminations within and across stimulus sets.

A longitudinal kernel analysis within each stimulus set and a cross-sectional kernel analysis across stimulus sets could document the decrements in the control exerted by stimulus control topographies unrelated to the contingencies of reinforcement, as well as the increments in control by relational topographies as participants learned new sets of unrelated conditional discriminations. Specifically, one hypothesis is that in early sets, many kernels would control responding by comparison position, by preference for particular comparisons, or by the discriminative function of the sample stimuli alone, with less control by relations between samples and comparisons. With successive stimulus sets, however, we would predict systematic decrements in control by the former SCTs and the emergence of predominant control by relations between samples and comparison, that is, the 100% and 000% SCTs. In the latter sets, both of these relational SCTs would have to occur with equal likelihood during the initial training blocks because a participant would not know which comparison was related to which sample stimulus. Thus, kernel analyses could operationalize the induction of attention to relevant relations among new sets of stimuli during the formation of learning set. This sort of analysis might also clarify the behavioral processes involved in other problem-solving strategies when a subject is faced with complex conditional discriminations. The data produced by a kernel analysis could also make contact with a number of theoretical accounts of discrimination learning, such as error-factor theory, hypothesis-based learning, and stimulus control topography coherence theory.

The kernel may also play a role as an independent variable. Typically, the establishment of a set of conditional discriminations such as AB, BC, and CD involves the randomized presentation of trials needed to establish each of the relations. When programmed in this manner, the four trials in an AB kernel would not be presented in a consecutive manner; likewise for the BC and CD kernels. It is possible, then, that the noncontiguous presentation of the trials in a kernel might slow the rate of acquisition of all of the conditional discriminations. This possibility could be evaluated with a training regimen in which AB, BC, and CD kernels were randomized but the four trials in a given kernel were presented consecutively, although in a randomized order with nonreplacement. A comparison of the rates and patterns of acquisition when training involved randomization by trial and by kernel would show whether one kernel-based parameter that influences the formation of arbitrary conditional discriminations would be the temporal contiguity of trials in a given kernel.

If a kernel is a unit of behavior, and the four trials in a kernel are presented concurrently, perhaps differential feedback should be presented at the end of each kernel rather than at the end of each trial. Whether this would influence the rate of acquiring conditional discriminations is an open question. On the one hand, the absence of trial-based feedback might be akin to attempting to establish an operant using an FR-4 schedule of reinforcement rather that an FR-1 schedule, which would predict retardation of acquisition. On the other hand, presentation of feedback on each trial could inadvertently strengthen SCTs that would interfere with the acquisition of control by the conditional relations between samples and comparisons. Again, these options can be resolved only with additional research.

Application of kernel analysis and developmental disabilities. Many studies have reported that individuals with developmental disabilities have difficulty with the formation of arbitrary or symbolic conditional discriminations (Eikeseth & Smith, 1992; Gollin, 1966; Green, 2001; McIlvane, Dube, Kledaras, & Iannaco, 1990; McIlvane, Kledaras, Killory-Andersen, & Sheiber, 1989; Perez-Gonzalez & Williams, 2002; Saunders & Spradlin, 1989). Some of these studies have suggested but not documented specific sources of stimulus control that presumably interfered with the establishment of behavioral control by relations between sample and comparison stimuli. A kernel analysis, then, could be used to identify the specific interfering sources of stimulus control, which in turn could lead to the development of focused remedial procedures to reduce these sources of interference. Theoretically, such a kernel-based diagnostic approach could facilitate the establishment of symbolic conditional relations.

Summary. A kernel analysis can be used to refine the study of stimulus control by the identification of all of aspects of stimuli that can influence responding in arbitrary matching to sample tasks. A few examples illustrated how two forms of kernel analysis illuminated the shifting forms of stimulus control that influenced responding during the acquisition of five concurrently trained arbitrary conditional discriminations. From a logical perspective, a kernel analysis should also be able to document the sources of stimulus control that govern responding during complex processes, such as the delayed emergence of equivalence and learning set, among others. Such data could also make contact with a number of theoretical accounts of discrimination learning. Finally, we considered how behavioral kernels might also influence the very establishment of conditional discriminations.

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