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USING AREA UNDER THE CURVE TO EXAMINE ACQUISITION OF TEMPORAL CONTROL

USO DEL ÁREA BAJO LA CURVA PARA EXAMINAR LA ADQUISICIÓN DEL CONTROL TEMPORAL

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Abstract

The present project applied area under the curve (AUC), a measure used to describe delay discounting functions (e.g., Myerson, Green, & Warasuwitharana, 2001) to the analysis of data from rats and pigeons obtained during the acquisition

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phase (i.e., first 10 sessions) in a peak-interval procedure (PIP). The variation of the AUC according to bin size was examined. Additionally, the AUC was correlated with other corresponding measures of temporal control: quarter lives and index of curvatures. In general, the AUC adequately reflected the changes in behavior during acquisition of a response pattern. Some limitations of these quantitative indices of temporal control are discussed. The application of AUC to quantify response patterns during acquisition during peak trials of a PIP can complement other types of data analysis conducted when using this procedure.

Keywords: area under the curve, index of curvature, quarter life, rats, pigeons, temporal control, peak-interval procedure

Resumen

Este proyecto presenta una aplicación del área bajo la curva (ABC), un índice usualmente utilizado para describir funciones de descuento de demora (e.g., Myerson, Green, & Warasuwitharana, 2001) al análisis de datos de ratas y pichones obtenidos durante la fase de adquisición (i.e., 10 primeras sesiones) de patrones de respuesta en un procedimiento de pico. La variación del ABC de acuerdo al tamaño de bin fue examinada. Adicionalmente, presentamos correlaciones entre el ABC, y sus correspondientes vidas cuartilares e índices de curvatura. En general, el ABC reflejó adecuadamente los cambios conductuales durante la fase de adquisición en el procedimiento de pico. Algunas limitaciones de los índices examinados son discutidas. La aplicación del ABC puede complementar otros tipos de análisis de datos que se utiliza con el procedimiento de pico.

Palabras Clave: área bajo la curva, índice de curvatura, vida cuartilar, ratas, pichones, control temporal, procedimiento de pico.

The study of the organization of behavior in time (i.e., temporal control) has been a hallmark of the experimental analysis of behavior. One procedure to assess temporal control is the peak-interval procedure (PIP; Roberts, 1981). In a PIP, subjects are typically pre-exposed to fixed-interval (FI) schedules of reinforcement (Balci, Gallistel, Allen, Frank, Gibson, & Brunner, 2009). After this preliminary training, longer trials (labeled peak trials) are interspersed randomly with instances of FI schedules. During peak trials, no reinforcers are provided. The response pattern for these trials resembles patterns of responding on the FI schedule: scallop-shaped curves, with a peak in response rate at the time when the reinforcer has been delivered during FI preliminary training; and a progressive decrease in

response rates following this peak. After repeated exposure to these peak trials, the pattern of responding resembles the shape of a Gaussian distribution: near the beginning of the trial responding is near zero and it progressively rises to a peak (around a target time) that progressively decreases again to low levels of responding as the trial ends. The PIP is useful in identifying the development of temporally-controlled response patterns (e.g., Balci et al., 2009; Kaiser, 2008; 2009) and also in revealing possible disruptions in temporal control (e.g., Grace & Nevin, 2000).

Typically, studies that use the PIP to measure temporal control focus on steady state performance (e.g., Grace & Nevin, 2000), that is, after some exposure to the procedure yields stable responding (Sidman, 1960/1988). A few (e.g., Abner, Edwards, Douglas, & Brunner, 2001 with mice; Balci et al., 2009 with mice; Kaiser, 2008; 2009 with rats; Kirkpatrick-Steger, Miller, Betti, & Wasserman, 1996 with pigeons), however, have focused on the acquisition of temporal control, specifically during the initial sessions of exposure to peak trials in a PIP. In the present studies, acquisition is defined qualitatively by visually judging the development of the Gaussian-like shape of the response distributions during the first 10 peak trials.

Kaiser (2008) examined the downward slope of the response curve during peak trials, specifically how responding declines after the target time (the peak) has been reached, and found that when the ratio of peak to FI trials is higher, acquisition is slower (i.e., more exposure is required to reach the normal-like shaped distribution described above). Kaiser examined response distributions as a function of time-based bins; this analysis allows for the quantification and visualization of the development of the normal-like shape of response patterns described above. In a follow up study, Kaiser (2009) confirmed that fewer peak trials facilitate the acquisition of responding during peak trials of PIP, even when response rates are controlled.

Two strains of mice (C57 & C3H) were used by Abner et al. (2001) to examine acquisition in a PIP, revealing that the former strain acquired the peaked pattern more quickly than the latter. Both strains, however, acquired these response patterns and were then exposed to pharmacological manipulations. Balci et al. (2009) used mice (strain C3H), who examined averaged and individual performance during the first 10 exposures to the PIP. They found that the development of the response curve during a PIP is not a gradual process. Rather, some took longer than others to acquire it, and also their response patterns looked different across time throughout acquisition; still each achieving a similar response pattern resembling a Gaussian distribution. This study highlighted the importance of examining individual data distributions, and the distinction between individual performances and averaging effects when studying acquisition.

Using pigeons, Kirkpatrick-Steger et al. (1996) found that, depending on peak-trial duration, more than one peak develops in the response patterns during initial exposure to the PIP. In general, a longer peak trial intermixed with FI trials in a PIP will lead to development of more than one peak; each peak, though, is characterized by a lower response rate, with the first one having the highest level of responding.

Independently, the studies described above included several species, but none of them directly compared two (or more) species in the acquisition of temporal control. All species, however, acquired a similar response pattern when using a PIP. In the present study, two species were exposed to the same PIP and the first 10 sessions were evaluated; this number of sessions was selected because previous studies show (e.g., Balci et al., 2009) that acquisition occurs between the first six to eight sessions; in addition both Abner et al. (2001) and Kaiser (2008, 2009) also examined acquisition using the first 10 sessions of exposure to the PIP.

Some quantitative measures of responding during the peak trials of the PIP focus on portions of the peak functions (e.g., start, stops, middles, as in Balci et al., 2009); from some of these measures, the difference between the start and the stop provides the spread, which captures more of the entire curve. Other quantitative measures such as the quarter life (QL, Herrnstein & Morse, 1957) and the index of curvature, (IC, Fry, Kelleher, & Cook, 1960) used to detect changes in FI-schedule performance (Richelle & Lejeune, 1980), could be applied to detect changes in sections of the peak function.

The QL is a summary index of the patterns resulting from exposure to an FI schedule (Gollub, 1964; Herrnstein & Morse, 1957); it is the percentage of the FI that has elapsed when 25% of the responses in that interval have occurred. A value lower than 25% indicates that relatively more responding occurred during the first quarter of the interval, and the opposite holds when the value of the QL is greater than 25%. The IC is a weighted area-under-the-curve measure (Critchfield et al., 2003); it reflects the extent and direction of the difference between the obtained data (i.e., the rate of responding across successive bins of the FI) and a straight line generated by a constant rate of responding throughout the interval (constant function). Specifically, the difference between the area under the obtained and constant functions is divided by the area of the constant function (Fry, et al., 1960). Positive values of the IC indicate positively accelerated curves, and negative values indicate negatively accelerated curves. Values between .25 and .75 are said to indicate typical FI scalloping.

The formula used to calculate the IC also assumes monotonic responding from the beginning to the end of the interval. Fry et al. (1960) stated that the IC can be misleading during intervals with few responses, which is true of all measures

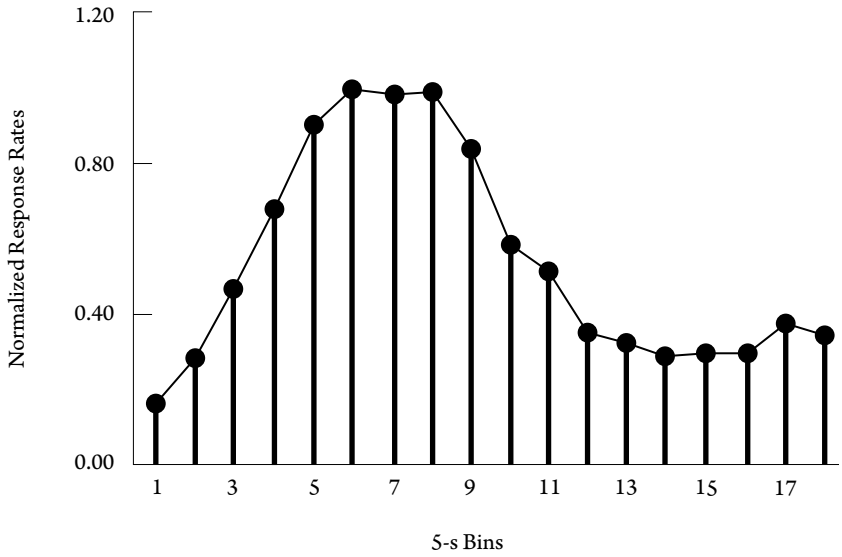

Figure 1. Normalized response rates for each 5-s bin. Trapezoids are drawn for each 5-s bin to calculate the AUC.

reviewed herein. Despite its limitations, Fry et al. reported that the IC is useful in tracking behavioral changes involved in acquisition of temporal control. Fry et al. also recommend including visual inspection of cumulative records to discard misleading indices and to also examine interval-by-interval patterns of responding.

These quantitative indices of temporal control have been directly compared (e.g., Dukich & Lee, 1973; Gollub, 1964). For instance, Gollub demonstrated that the QL is positively correlated with the IC. Dukich and Lee (1973) evaluated relations between QL and other indices of FI performance such as running rate, post-reinforcement pause (PRP), elapsed time to the fourth response, and average running rate. The PRP and the time to the fourth response were positively correlated with the QL, leading them to conclude that the QL is sensitive to changes in response patterning.

Myerson, Green, and Warasuwitharana (2001) described the use of AUC to quantify delay-discounting functions. To calculate AUC, functions are divided into trapezoids by dropping lines from the function to the x-axis as shown in Figure 1. The area of these trapezoids is calculated and summed; this sum is then divided by the total area of the graph (i.e., the product of the maximum values on the x- and y-axes) to determine the AUC. This index is useful because it provides a single number that characterizes the function (Odum, 2011). Although AUC has been

used extensively in the analysis of delay discounting, we propose that it also complements the analysis of temporal control, and in particular may be a valuable tool in describing the acquisition of such control.

Elcoro et al. (2014) used the AUC to examine the effect of 6-hydroxydopamine (6-OHDA) lesions in the medial prefrontal cortex of rats trained on PIP. Specifically, rats in a sham group recovered to initial levels of PIP performance (as shown by comparable AUC values before and after the lesion) while data obtained from the rats that received the 6-OHDA lesions yielded lower AUC values during the PIP after the lesions. Although this study did not focus on the acquisition of response patterns, but rather on established patterns of responding using a PIP (i.e., using the five last sessions of 38 sessions before the lesions, and the last five sessions of 38 sessions after the lesions), the AUC proved accurate and useful in tracking recovery and alterations in responding. Although the peak times were unaltered when comparing between sham and 6-OHDA groups, overall response rates compared to the sham group were lower in the 6-OHDA group. Additionally, the response curves in the peak trials were flatter for the lesioned as compared to the sham group, even after extended training on the PIP after the lesions were made.

The primary purpose of this study was to explore the parameters of the AUC as a measure of the acquisition temporal control. A secondary purpose is to compare the AUC as an index of temporal control with other quantitative measures. A third purpose is to directly compare two species (using the same procedure and analysis) during the first 10 sessions of the PIP. To do this the first 10 sessions of a PIP were examined—in Study 1 with rats and in Study 2 with pigeons—and AUC was calculated. The effects of varying bin size on the calculation of the AUC were also examined, and then the correlations between AUC, IC, and QL were evaluated.

Study 1

Method

Subjects

Eleven experimentally-naïve male Sprague Dawley (Charles River, NC) rats, approximately 6 months old at the start of the experiment, were housed individually in a room kept at a constant temperature and illuminated following a 12-hr light/dark cycle. Post-session feeding was provided accordingly to keep weights within a healthy range. Water was available at all times with the exception of when the subjects were in the experimental sessions.

Apparatus

Six modular operant conditioning chambers for rats (Coulbourn Inst., PA), each contained in a sound-attenuating enclosure, were employed. Each chamber was 31 cm by 26.4 cm by 32.8 cm and had modular walls with filler panels and a stainless steel standard response lever requiring a force of 0.25 N to operate. The response lever, protruded 2 cm from the wall, was 3.5 cm wide, and was placed at a height of 6.6 cm from the floor. The center of the lever was 3.2 cm from the feeder tray on the same wall. A houselight was in the upper-right corner of the same wall as the lever and the feeder trough. The trough was divided into two compartments, one for liquid reinforcers (on the left) and the other for dry (food pellet) reinforcers on the right. Only the dry reinforcer portion of the tray was used in this experiment and was illuminated each time a reinforcer was delivered for 3 s (and simultaneously the houselights was turn off for the same duration). Sucrose-based pellets (45-mg) functioned as reinforcers. Real-time data collection was conducted and all experimental routines were programmed using Graphic State II (Coulbourn Inst., PA) software.

Procedure

Prior to exposure to the FI schedule, all rats were first exposed to the operant chamber for habituation, followed by variable-time 60-s schedule of food delivery for feeder training and then exposed to a fixed-ratio (FR)1 to FR 5, then FI 5-30 s. All rats were exposed to fifteen sessions of FI 30-s schedules of reinforcement until 60 reinforcers were collected in each such session. This was followed by 10 consecutive sessions of exposure to the PIP that consisted of FI 30-s trials, with peak trials of 90 s, each separated by a 20-s inter-trial interval (blackout). In each session, 42 reinforcers were delivered according to an FI schedule. Peak trials occurred randomly between the FIs for a total of 18 peak trials per session, with a limit of three peak trials occurring in a row.

Data Analysis

Normalized response distributions and area under the curve. The responses occurring during the 90-s peak trial (in 1-s bins) were summed across the 18 peak trials per session to create one peak-trial function per rat, per session. The data collected were collected in 1-s bins. To convert 1-s bins into 5-s bins, the response rates for the first five bins were averaged, and the same was done for the other bin sizes examined.

The data points of a peak-trial function were first normalized, that is, the mean response rate for each 5-s bin of the peak trial was divided by the maximum average

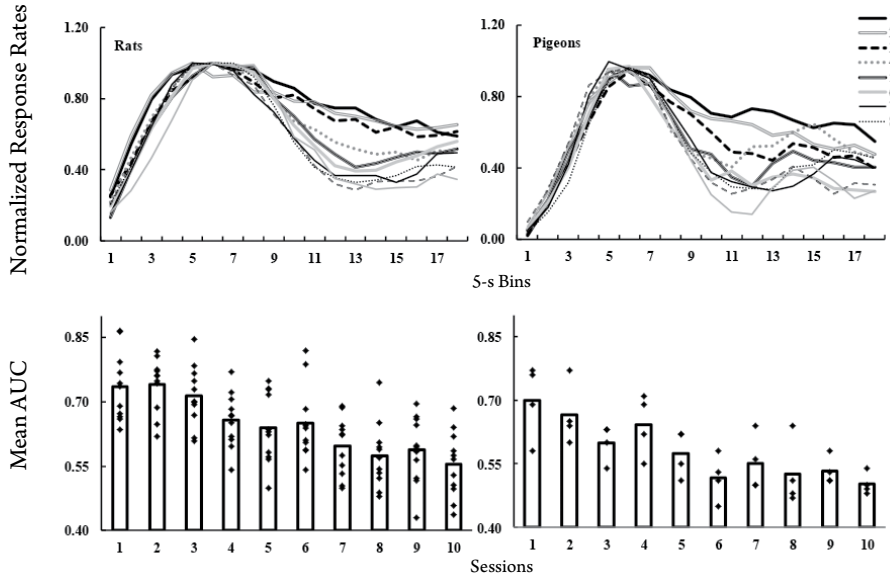

Figure 2. Normalized response rates per 5-s bins for 10 sessions (top graphs) and corresponding mean AUC for each response function from the top graph (bottom graph) per session. Shadings and line styles presented on the legend identify each function per session (1-10). Bars correspond to each mean AUC and filled diamonds for individual rats (on the left) and pigeons (on the right) mean AUCs for that session.

response rate within that peak trial; these are expressed as normalized response rates per 5-s bin. This normalization of all distributions allows for direct comparisons between sessions and across species.

The corresponding area under the curve (AUC) for each function for each session was calculated as described by Myerson et al. (2001). The AUC was calculated by dividing the normalized response distributions described above into trapezoids, with one trapezoid for each bin as shown Figure 1. The areas of all of the trapezoids were calculated, summed, and divided by the product of the maximum value of the x- and y-axes. Dividing by the maximum of the graph area provided the proportion of the figure that falls below the function.

Bin size for calculation of area under the curve. One goal of this study was to evaluate AUC as a function of bin size. To do this, varying bin sizes (1, 3, 5, and 10 s) were used to obtain the AUC values. Mean AUC values and corresponding SEMs are compared across four bin sizes as shown in Figure 3.

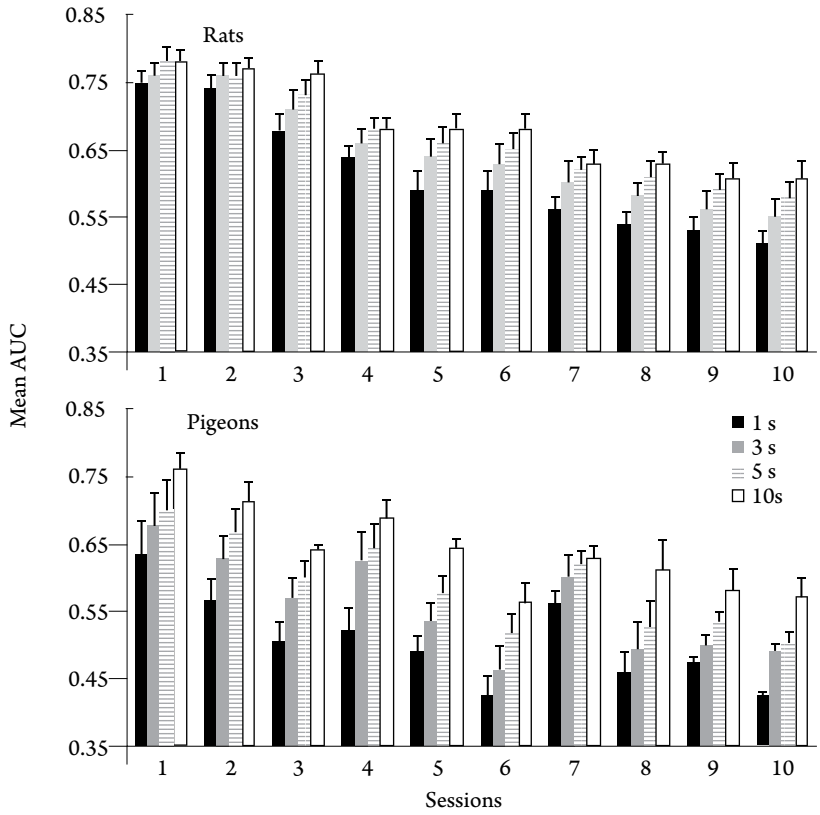

Figure 3. Mean AUC per session (x axis) compared by bin size (1, 3, 5, and 10-s). Lines extending from bars represent standard errors of the means.

The 5-s bin size was employed for the AUC depicted on Figure 2 because it provided the clearest depiction of progressive shaping of the response curve similar to other publications previously referenced in the present manuscript. Lower size bins (1-3 s) made this pattern of the peak function less discernible and more difficult to detect by visual inspection. Alternatively, a bin size of 10 s smoothed the curve too much, eliminating some of the variations in the pattern of responding during acquisition. In addition, Wilcoxon sign-ranked tests were used to compare AUCs obtained across different bin size.

Comparing area under the curve, quarter life, and index of curvature. Another goal of this study was also to assess how AUC fits within the context of other measures of temporally controlled patterns. To this end, AUC was compared

with QL and IC values using the same data. The QLs and ICs were calculated using 1-s bins because this bin size (compared to the others evaluated, also 3, 5, 10 s, data not shown) provided sufficient variation between indices to reflect changes in the pattern of behavior; in this case a 5-s bin provides little variability between measures. This is a different selection of bin size compared to the one that was described above (for depiction of response distributions and calculation of AUC); thus depending on the type of analysis, bin selection may change. It should also be noted that these two measures, QL and IC, are based data from the first third (first 30 s) of the peak-trial function, compared to the AUC that takes data from the entire function. This follows the characteristic use of these measures to examine the development of the scalloped pattern in a FI schedule of reinforcement (as in Critchfield, Haley, Sabo, Colbert, & Macropoulis, 2003; Gollub, 1964). The QL and IC were applied to the patterns of the responses occurring during the first 30 s of the trial (the duration of the peak trial in this study was 90s).

The response distributions for the first 30 s of the peak trial were transformed to cumulative distributions then normalized dividing each bin of the cumulative distribution by the total number of responses emitted during this time. After that, the proportion of the interval (first 30 s of the 90-s peak trial) in which 25% of the responses occurred was identified. This was done for each rat for each session, then averaged across rats by session, as shown in Table 1 (with corresponding SEMs).

The IC was calculated as described by Fry et al. (1960) and Odum and Schaal (2000), for each rat, for each session, using the following formula:

$$I = 29R30 - \frac{2(R1 + R2 + R3 + \cdots R29)}{30R30}$$

where R1 is the total number of responses in the first bin, R2 the number of responses in the second bin plus number of responses in the first bin, and so on until the thirtieth bin; R30 is the total number of responses in all bins. Negative numbers indicated accumulation of responses near the initial bins and positive responses indicate more accumulation towards the later bins (-.75 to +.75). These measures were averaged across rats by session. These data are shown in Table 1 along with their corresponding standard error of the mean (SEM).

To directly compare AUC, QL, and IC, z-scores were obtained for reach of the corresponding measures for each rat (as in Hinojosa, Sheu, & Michel, 2003), during each session. These session averages are shown in Figure 4. Values between -1.65 and +1.65 were used to establish differences above chance by 5%, that is, if values

Table 1.

Means with SEMs in Parentheses for AUC, QL and ICs for Each Session.

Sessions	Rats			Pigeons		
	AUC	QL	IC	AUC	QL	IC
1	.74 (.08)	.40 (.06)	.19 (.08)	.70 (.04)	.51 (.05)	.41 (.06)
2	.74 (.06)	.39 (.04)	.17 (.06)	.67 (.04)	.49 (.03)	.40 (.06)
3	.71 (.07)	.43 (.07)	.22 (.09)	.60 (.02)	.53 (.05)	.43 (.06)
4	.66 (.06)	.43 (.06)	.24 (.07)	.64 (.04)	.47 (.06)	.37 (.06)
5	.64 (.08)	.45 (.06)	.26 (.08)	.58 (.03)	.47 (.05)	.36 (.06)
6	.64 (.09)	.46 (.06)	.26 (.08)	.52 (.03)	.51 (.04)	.40 (.06)
7	.59 (.07)	.47 (.06)	.27 (.08)	.55 (.03)	.50 (.05)	.41 (.06)
8	.57 (.05)	.46 (.07)	.25 (.09)	.53 (.04)	.52 (.05)	.45 (.06)
9	.59 (.08)	.45 (.07)	.26 (.10)	.53 (.02)	.47 (.03)	.34 (.05)
10	.55 (.08)	.49 (.07)	.31 (.12)	.50 (.01)	.47 (.05)	.35 (.05)

varied by more of the values between these cutoffs, then there was a significant difference (Hinojosa et al., 2003). Pearson correlation coefficients were calculated between AUC, QL, and IC.

Results

Table 1 shows the mean values across rats for each of the 10 PIP sessions for AUC, QL, and IC and corresponding standard errors of the mean (SEM). In general, the variability across rats and across sessions, within these measures was consistently low (SEMs ranged between .04 and .12 in all measures).

The resulting response distributions are shown in the top graphs of Figure 2. Each graph shows 10 functions (distinguished by line patterns) that correspond to the first 10 sessions of exposure to the PIP. Such functions allow for visual analysis of the development of the response patterns across sessions. The lower graphs show, for each session, the corresponding AUC for each normalized response distribution (depicted in the upper graphs) and also the AUC for individual subjects represented by diamonds. This analysis allows a comparison of individual versus averaged AUC across sessions.

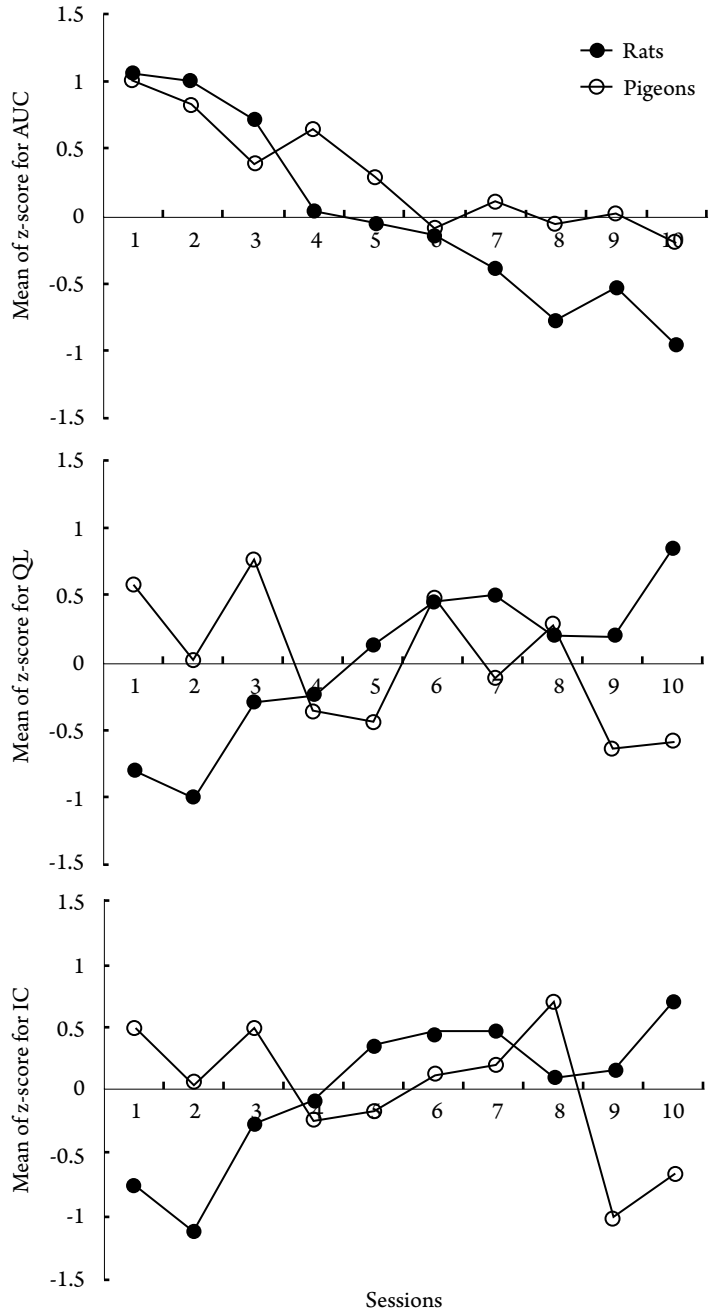

Figure 4. Mean z-scores for AUC, QL, IC for each session for rats and pigeons.

The response distribution shown as the top graphs in Figure 2, shows that rats' responding peaked at about 30 s and progressively decreased thereafter showing that responding peaks, then less responding occurs in the bins located at both extremes of the distributions. This pattern describes a Gaussian distribution. The progressive reduction in responding after the peak coincides with the decreasing trend in AUC values shown in the bottom of Figure 2. The diamonds superimposed on the bars (that represent average data) represent individual AUC. As the sessions progressed, the values of the AUCs generally decreased, from a mean of .74 (SEM = .08) to .55 (SEM = .08). The variability of the AUCs across sessions was consistent (range of SEM was from .05 to .09) and generally low. There was a general decrease in AUC for individual rats.

As shown in Figure 3, when the bin size was smallest, on average, the AUC values were also smallest (M = .61, SEM = .03). Wilcoxon sign-ranked tests (two tailed) revealed statistically significant differences between AUC values obtained with different bin sizes. More specifically, for the rats, the following paired comparisons across bin sizes each yielded statistically significant differences: Bins 1 vs. 3 s (z = -2.825, p = .005), bins 1 vs. 5 s (z = -2.818, p = .005), bins 1 vs. 10 s (z = -2.814, p = .05), bins 3 vs. 5 s (z = -2.762, p =.005), bins 3 vs. 10 s (z = -2.823, p = .005) and bins 5 vs. 10 s (z = -2.549, p =.011).

The pattern of AUCs for rats, in Figure 4 follows a decreasing trend as a function of sessions of exposure to the PIP. In the case of AUCs, a decreasing pattern of AUCs (also shown as the lower graphs in Figure 2) corresponds to the development of the peak function and, in general, as sessions progress, the AUC decreases. For both QL and IC, increasing values indicate more of the responses being accumulated at the end of the interval, in this case, most of the response progressively accumulated toward the peak area, that is, toward the 30-s point of the 90-s peak trial. The pattern of QL and IC for the rats follows an increasing trend. Correspondingly, Pearson correlation coefficients yielded a high negative correlation between AUC and QL (r = -.93, p < .01), and also between AUC and IC (r = -.91, p < .01). There was a high positive correlation between the QL and IC (r = .98, p < .01).

Discussion

The changes in the response distributions of the rats during the first 10 sessions of the PIP, shown in the top left graph of Figure 2, are similar to those observed by Abner et al. (2001), Balci et al. (2009), Kaiser (2008, 2009), and Kirkpatrick-Stegner et al. (1996). The AUC, as calculated by Myerson et al. (2001), accurately

tracked behavioral changes during the acquisition of temporal control during a PIP (bottom left of Figure 2) by showing that the area of these response functions decreases as a function of sessions.

The differences in the AUC as a function of bin size indicate that bin selection is an important consideration in the measurement of temporal control acquisition under the PIP. The selection of bin size is guided by seeking order in the data (Sidman, 1960/1988). In the present study, the selection of 5-s bins was guided by the selection of bin size that allowed for orderly observations of the changes in the shape of the curve (top left graph in Figure 2). The bin size is consistent between AUC selected and the curves examined in Figure 2. Despite some of the significant differences found in AUC calculated with different bin sizes (see Figure 3), the progressive decrease in AUC values across sessions was maintained across bin size.

The QL and IC were highly and positively correlated as previously reported by Dukich and Lee (1973) and Gollub (1964), confirming that such measures provide comparable information. The strong negative correlation between the AUC and both QL and IC corresponds to the portions of the peak-trial function that each measure targets; the QL and IC values increase (as shown in Figure 4) as function of sessions given that responding accumulates towards the peak of the function (around 30 s) and precisely these two measures are derived from responding during the first 30 s of the peak trial, while AUC decreases given that it is derived from data of the entire peak-trial function.

Overall the responding of rats is changed systematically as a function of exposure to the PIP. As in previous studies by Abner et al. (2001), Balci et al. (2009), Kaiser (2008, 2009), and Kirkpatrick-Steger et al. (1996), such orderly changes can be observed within the first 10 sessions.

Study 2

Method

Subjects

Four white Carneau male pigeons (Palmetto Pigeon Plant, SC) with prior history with various schedules of positive reinforcement were maintained at 80% of their free-feeding body weight. The pigeons were housed individually with free access to water and health grit in a housing colony kept in a12-hr light/dark cycle and at a constant temperature.

Apparatus

Two operant conditioning chambers in a sound-attenuating enclosure were used. Each chamber was 32 cm long by 30 cm high by 30 cm wide and had an aluminum work panel as a wall. A 2.54 cm diameter response key was in the center of the aluminum panel and was transilluminated with a white light. Three seconds access to mixed grain delivered from a Gerbrands food magazine functioned as a reinforcer. A houselight was used to illuminate the chamber and a ventilation fan was on at all times during the experiment. Experimental routines and data collection were controlled by Med-Associates® software and interface.

Procedure

The procedure was as described in Study 1, except that key pecking was the operant response, and 3-s access to mixed grain functioned as a reinforcer. Thus, the terminal schedule was FI 30 s, and the peak trials were 90 s long. In addition, pretraining with FI 30-s schedules prior to implementing the PIP, consisted of 24-27 sessions; each session ended after 40 reinforcers were obtained.

Data Analysis

As described for Study 1.

Results

The data in Table 1 for the pigeons show that the variability across means of the three dependent measures shown is low (SEMs ranged between .01 and .06 in all measures). The top right graph of Figure 2 shows the peak-trial curves for pigeons during the first 10 session of exposure to the PIP. A progressive decrease in responding after the peak time (30 s) occurred across sessions. Correspondingly, as sessions progressed, the values of the AUCs generally decreased, from a mean of .70 (*SEM* =.04) to .50 (*SEM* = .01). The diamonds superimposed on the bars (that represent the average data) represent individual AUCs and show that the decrease in AUCs across sessions also occurred in individual pigeons.

As shown in the lower graph of Figure 3, when the bin size was smallest, on average, the AUC values were also lowest (M = .49, *SEM* =.05). Wilcoxon sign-ranked test (two tailed) revealed statistically significant differences between each of the six pairs of bin sizes. Each comparison yielded the same values, z = -2.78, p = .005. Thus,

there was a significant difference in AUC across each of the pairs of bins, with the AUC increasing with a corresponding increase in bin size.

The pattern of AUCs for pigeons in Figure 4 follows a decreasing trend across successive sessions, which is in accord with the acquisition of the response function depicted on Figure 2. The correlation between AUC and QL for pigeons was .65 (p = .04), between AUC and IC .77 (p =.01), and between QL and IC positive and high (r = .93, p < .01).

Discussion

The changes observed in the response distributions during the first 10 sessions of the PIP, depicted on the top right of Figure 2, are comparable to those obtained by Abner et al. (2001), Balci et al. (2009), Kaiser (2008; 2009), and Kirkpatrick-Stegner et al. (1996). The AUC (as calculated by Myerson et al., 2001) precisely tracked changes during the acquisition process of responding on peak trials (bottom right graph of Figure 2), as the area of these response functions decreases as a function of sessions.

There were differences across bin size when calculating the AUC. In the present study the 5-s bins was selected because such size allowed for orderly observations of the changes in the shape of the curve (top right graph of Figure 2). The bin size is consistent between AUC selected and the curves shown in Figure 2. The consistent decrease in AUC values across sessions was maintained across bin sizes (see Figure 3).

Correlations between QL and IC were high and positive, as found previously by Dukich and Lee (1973) and Gollub (1964). In responding by pigeons, the correlations between AUC and QL and between AUC and IC were moderate and positive; as shown in Figure 4.

Overall the responding of pigeons changes systematically as a function of exposure to the PIP, during the first 10 sessions (as in Abner et al., 2001; Balci et al., 2009; Kaiser, 2008, 2009; Kirkpatrick-Steger et al., 1996). The mathematical indices used provide useful information and also examining the actual response distributions is a central part of the analysis.

General Discussion

For both rats and pigeons, the values of the AUC decreased across successive sessions of exposure to the PIP. These decreasing values are consistent with the

shapes of the peak-trial curves shown in Figure 2 and reflect the development of the downward slope in the peak-trial functions previously described by Kaiser (2008, 2009). In both species the acquisition of responding in the peak trials can be accurately described by calculating AUC (cf. Myerson et al., 2001).

The AUC accurately tracked changes in behavior during acquisition. The consistent decrease in AUC values as a function of sessions of exposure to the PIP was evident when the data for both rats and pigeons were averaged and also when examining values for individual subjects (see Figure 2). Such findings are consistent with the application of the AUC by Elcoro et al. (2014). The QL and the IC also have been used to describe the functions generated by FI schedules; here, they were used to describe the shape of the first 30 s of the 90-s peak trial. The QL for the 10 days of acquisition was negatively correlated with AUC, which was expected given the AUC decreased as sessions progressed and the QLs increased. Also, as in Gollub (1964), in the present studies the QLs and ICs were highly and positively correlated.

Although the present analysis shows that the AUC is a potential additional measure to examine responding in a PIP, there are few theoretical and procedural considerations meriting attention. Although in the context of the study of delay-discounting (Myerson et al., 2001), the AUC has been described as a theoretically neutral index, not requiring that the functions have any particular shape (cf. Odum, 2011), such theoretical neutrality is compromised when using this index for the evaluation and understanding of temporal control. This is because the data are normalized to calculate the AUC; this is a necessary step to provide a basis of comparison, otherwise the data obtained in a peak trial are too variable and hard to interpret and compare across individuals and across sessions. This was done because in the present study the main interest is the examination of response patterns generated during peak trials of a PIP. This is a similar situation to how the data are organized for the calculation of the IC, as it requires a monotonically increasing function (resulting from accumulating the values of the bins of the peak-trial distribution) to compare with the obtained data.

An important procedural aspect is the selection of bin sizes when organizing the data in response distribution (as in the top of Figure 2) and when using such data to calculate AUC. In the present analysis, increasing the bin values (from 1 to 10-s) or, in other words, smoothing the curves, impacted AUC values (see Figure 3). Using smaller bin sizes may provide a more accurate and sensitive measure of the AUC, as the smaller bins provide a closer approximation to the shape of the curve that is closer to the raw data obtained using a more sensitive, time-based unit. Using

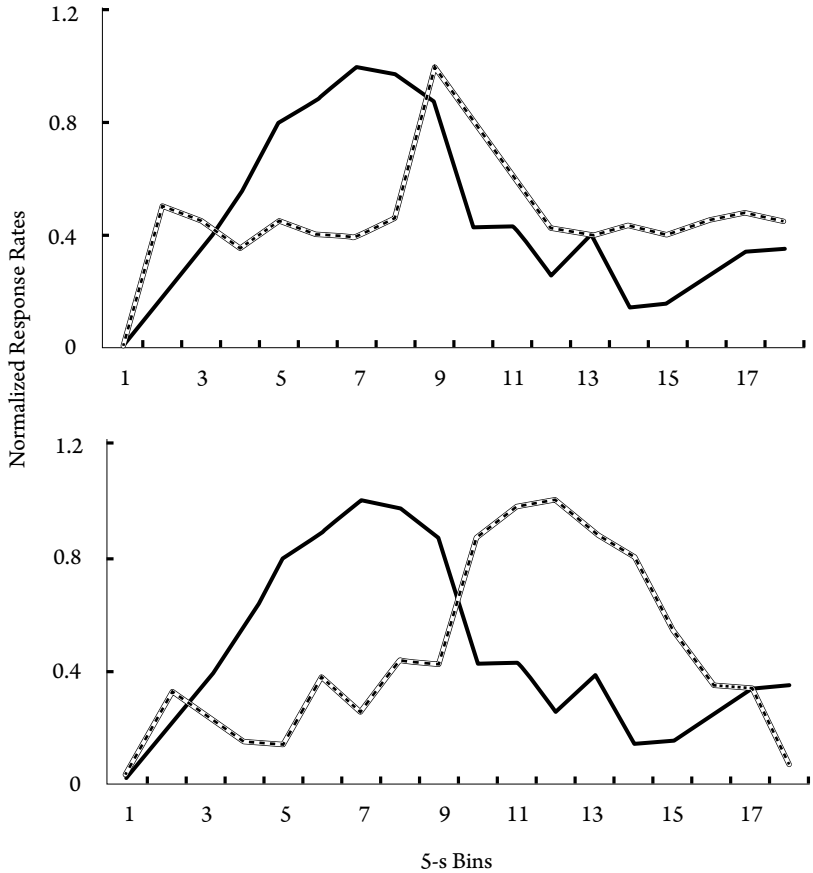

Figure 5. Examples of distributions created with hypothetical data. The top graph displays two different shapes of a response distribution; each curve yields the same AUC. The bottom graph displays symmetrical curves with identical AUC.

larger bins requires more smoothing of the function and may obscure some of the finer details in the development of response patterns. At the same time, it may be hard to capture changes of more global nature if the bin size is too small. Thus, we suggest that researchers should use their judgment to decide which bin size would be most appropriate, perhaps evaluating with multiple bin sizes to identify the most useful level of analysis.

The same limitation describe above is present when calculating both QL and IC. In discussing the QL as an index of response patterning, Dukich and Lee (1973) suggest that the QL can change in a particular direction (e.g., decrease)

between conditions, but that this change can also be due to a variety of changes in response patterning (e.g., running rate decreasing for some subjects and increasing for others). Thus, the QL may grossly describe the shift in behavior but may not be sufficient to identify the mechanism of that change, or to accurately reflect the change in response pattern. The same may be said of the AUC; it is possible that there are several functions with different shapes and the same AUC values as shown in Figure 5.

A situation such as the one depicted using hypothetical data in Figure 5 can be properly addressed if multiple measures of responding are available (not only the AUC). More specifically the observation of the distribution of responses across time (peak-trial curves) provides guidance in assessing the accuracy of quantitative indices such as the QL, IC, and AUC (Fry et al., 1960). One benefit of these quantitative indices is that they provide a summary (Odum, 2011) measure that allows more accessible comparisons as the one shown in Figure 4 (across indices, across pigeons), and provides opportunities for statistical analyses.

In the present analysis the numbers in each group to calculate average measures was different: we used the data from 11 rats and 4 pigeons. Such difference in *n* may affect the variability of some measures as the QL and IC for pigeons, shown in Figure 4. More specifically, these two measures, in rats, increased as function of sessions, which is expected given the pattern of the first 30 s responding in a 90-s peak trial. Such pattern is not quite as clear for pigeons, in which QL and IC values are more variable across sessions (as shown in Figure 4).

The two main contributions of the present study are: (1) the examination of a novel quantitative measure to study a behavioral process such as acquisition in a PIP not as often examined (compared to steady states), and (2) the direct comparison of two species during acquisition of responding in a PIP. The acquisition process in both rats and pigeons was similar during the first 10 sessions and the AUC was shown to be a viable additional quantitative index to examine responding in the PIP. Using multiple methods of evaluating the data (i.e., more than one quantitative index accompanied by visual inspection of the data, as stated by Fry et al., 1960) is beneficial and provides the most complete description of obtained data.

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