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RISK-SENSITIVE CHOICE IN HUMANS AS A FUNCTION OF AN EARNINGS BUDGET

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Risky choice in 3 adult humans was investigated across procedural manipulations designed to model energy-budget manipulations conducted with nonhumans. Subjects were presented with repeated choices between a fixed and a variable number of points. An energy budget was simulated by use of an *earnings budget*, defined as the number of points needed within a block of trials for points to be exchanged for money. During positive earnings-budget conditions, exclusive preference for the fixed option met the earnings requirement. During negative earnings-budget conditions, exclusive preference for the certain option did not meet the earnings requirement, but choice for the variable option met the requirement probabilistically. Choice was generally risk averse (the fixed option was preferred) when the earnings budget was positive and risk prone (the variable option was preferred) when the earnings budget was negative. Furthermore, choice was most risk prone during negative earnings-budget conditions in which the earnings requirement was most stringent. Local choice patterns were also frequently consistent with the predictions of a dynamic optimization model, indicating that choice was simultaneously sensitive to short-term choice contingencies, current point earnings, and the earnings requirement. Overall, these results show that the patterns of risky choice generated by energy-budget variables can also be produced by choice contingencies that do not involve immediate survival, and that risky choice in humans may be similar to that shown in nonhumans when choice is studied under analogous experimental conditions.

Key words: concurrent schedules, risky choice, optimal foraging, energy budgets, adult humans, key press, points exchangeable for money

The term *risky choice* has been used to refer to behavior in relation to environmental variability. Preference for fixed (i.e., constant) or variable alternatives has been described as *risk sensitivity* (Kacelnik & Bateson, 1996). Risk sensitivity may take one of three forms. If a fixed option is preferred to a variable option, choice is said to be *risk averse.* If a variable option is preferred to a fixed option, choice is said to be *risk prone.* Finally, if no strong preference for either option occurs, choice is said to be *risk neutral* or *indifferent.*

Risky choice has been investigated by researchers from a variety of scientific disciplines including psychology, behavioral ecology, anthropology, and economics. This research has shown that behavior is sensitive to environmental variability under a wide variety of conditions. An overview of this research reveals, however, an apparent discrepancy between human and nonhuman risk sensitivity. In general, humans tend to show greater risk aversion than do nonhumans (e.g., Kahneman & Tversky, 1979; Kohn, Kohn, & Staddon, 1992; Rachlin, Logue, Gibbon, & Frankel, 1986; Schmitt & Whitmeyer, 1990; Schneider, 1992; Schneider & Lopes, 1986; Silberberg, Murray, Christensen, & Asano, 1988; and see Kacelnik & Bateson, 1996, for a recent review of nonhuman risky-choice research). It is difficult, however, to compare performances of humans and nonhumans due to procedural differences. Thus, inconsistencies in risky choice in humans and nonhumans may have less to do with species differences than with differences in the methods by which choice is typically assessed.

One type of variable that has been shown

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by behavioral ecologists to produce reliable effects on risky choice in nonhumans, but that has not yet been examined in humans, concerns changes in an organism's energy budget. *Energy budget* refers to the energy status of an organism in relation to its energy requirements (Bateson & Kacelnik, 1998). In certain species, individuals must accumulate sufficient energy reserves while foraging to survive a period in which foraging is impossible (e.g., overnight). If reserves are high or the mean rate of food intake is sufficient to meet the energy requirement, the energy budget is positive. If reserves are low or the mean rate of food intake is insufficient to meet the energy requirement, the energy budget is negative.

These relations were formalized by Stephens (1981). The model was designed to predict foraging-related choices between two food options when R units of food are needed to survive overnight. Both food options have the same mean value, but have different variances. Ignoring expenditures, a forager's daily energy budget can be described as

$$\mu \cdot n + S_n > R \quad \text{(positive energy budget)}$$

and

$$\mu \cdot n + S_n < R \quad \text{(negative energy budget)}, \tag{1}$$

where S_n is energy reserves, μ is mean food intake per time interval, and n is the number of time intervals in the foraging period.

To predict choice under positive and negative energy budgets, Stephens (1981) assumed that only one foraging choice occurred each day and that at the end of the day the forager would have S_0 reserves. This amount, determined by the choice option, was assumed to be distributed normally with mean μ and variance s^2. Fitness was assumed to be a step function of reserves. That is, all reserve levels below R had a fitness value of zero, and all reserves above R had the same (nonzero) value. Because S_0 was normally distributed, R could be converted into a z score:

$$z = (R - \mu)/s.$$

The probability of survival at the end of the day was calculated as

$$P(S_0 > R) = 1 - F(z),$$

where $F(z)$ is the cumulative distribution of the normal curve. Because $F(z)$ increases as z increases, minimizing the value of z increases the probability of survival. When the energy budget is positive, z is minimized by decreasing the variability. Conversely, when the energy budget is negative, z is minimized by increasing the variability. Thus, choice should be risk averse when the energy budget is positive and risk prone when the energy budget is negative (Stephens & Krebs, 1986).

This model, called the extreme variance rule, z-score model, or energy-budget rule, predicts choice between options having the same mean value. It can also be extended to choices in which options differ in both their mean values and variances (Stephens & Charnov, 1982). It should be noted that the energy-budget rule, based upon overnight survival, is only one type of risk-sensitive foraging model (see McNamara & Houston, 1992). The energy-budget rule will be emphasized here because this model has received the greatest amount of empirical support.

The first experiment to demonstrate shifts in risk sensitivity with changes in energy budget was conducted by Caraco, Martindale, and Whittam (1980). Six yellow-eyed juncos were given repeated choices between two feeding stations delivering either a constant or variable number of seeds. The probability distribution of the variable option was bivalued. Daily energy requirements were determined by measuring metabolic rates and the rate of food intake. During positive energy-budget conditions, subjects were deprived of food for 1 hr prior to experimental sessions and seeds were delivered at a mean rate that exceeded daily requirements. During negative energy-budget conditions, subjects were deprived for 4 hr and seeds were delivered at a mean rate that fell below daily requirements. Caraco et al. found that choice was risk averse during positive energy-budget conditions and risk prone during negative energy-budget conditions. Thus, energy budget influenced risk sensitivity in a manner consistent with the energy-budget rule. A number of subsequent studies with fish (Croy & Hughes, 1991; Young, Clayton, & Barnard, 1990), bumblebees (Cartar, 1991; Cartar & Dill, 1990), shrews (Barnard & Brown, 1985), and small birds, including white-crowned sparrows (Caraco, 1983) and dark-eyed juncos (Caraco, 1981), have demonstrated shifts in risk sensitivity with changes in energy budget (for reviews, see Bateson & Kacelnik, 1998; Kacelnik & Bateson, 1996; Real & Caraco, 1986).

Not all experiments in which energy budgets have been manipulated have produced complete shifts from risk aversion to risk proneness as energy budgets were changed from positive to negative. In several studies, only the degree of risk aversion changed (Hamm & Shettleworth, 1987; Ito, Takatsuru, & Saeki, 2000). That is, choice remained risk averse across conditions but became less risk averse under negative energy-budget conditions. Other studies have shown no change in risk sensitivity across changes in energy budget (Banschbach & Waddington, 1994; Battalio, Kagel, & McDonald, 1985), whereas still others have shown changes in risk sensitivity in the direction opposite to that predicted by the energy-budget rule (e.g., Hastjarjo, Silberberg, & Hursh, 1990; Lawes & Perrin, 1995). Thus, although not consistent with all available data, the energy-budget rule provides a reasonably good account of risky choice in many species, and it makes predictions about the effects of energy budgets no other choice models make (see Bateson & Kacelnik, 1998).

No laboratory studies have yet manipulated energy budgets in humans. One of the main obstacles to studying energy-budget effects in humans is the problem of manipulating food intake. The effects of negative energy budgets are normally studied by restricting food access and presenting food reinforcers during experimental sessions at a rate that is insufficient to meet energy requirements. Even if human participants agreed to restrict food intake and deprivation levels could be verified, deprivation levels would necessarily be far below those required to induce genuinely negative energy budgets. It may be possible, however, to create experimental procedures that model important features of an energy budget without using food or life–death choices, by employing a monetary earnings requirement in place of an energy requirement.

Although optimization models typically define *optimal* in terms of energy gain (a correlate of reproductive fitness), the predictions of such models can be extended to situations in which outcomes are monetary earnings (Winterhalder & Smith, 2000). In the present research, the reinforcement contingencies established by the relation between choice payoffs, accumulated earnings, and the earnings requirement (an earnings budget) were manipulated to simulate positive and negative energy budgets. The objective was to develop a procedure to assess risk sensitivity in humans across manipulations that are analogous to energy-budget manipulations conducted with nonhumans, and to evaluate the descriptive adequacy of the energy-budget model as an account of human choice.

Because the energy-budget rule predicts only one pattern of risk sensitivity across an entire foraging period (i.e., exclusive preference for the fixed or variable options), it has been called a static optimization model (see Kacelnik & Bateson, 1996; Krebs & Kacelnik, 1991). However, switching between the fixed and variable options as a function of current energy state may sometimes be better than persisting with a single choice option (e.g., Houston, 1991; Houston & McNamara, 1982; McNamara & Houston, 1987; Real & Caraco, 1986). For example, if a forager whose energy budget is currently negative experiences a period of high gain, then switching from the variable option to the fixed option may increase the probability of survival. Thus, another goal of the present research was to provide a detailed analysis of choice patterns within, as well as across, choice periods.

When choice varies as a function of current state, and state varies as a function of previous choices, then a dynamic optimization model rather than a static model is needed to predict optimal choice patterns (Houston & McNamara, 1988; Mangel & Clark, 1988). Dynamic optimization models, designed to predict local regularities in choice patterns, provide a more detailed description of behavior than static models designed to predict more global outcomes (Krebs & Kacelnik, 1991). The major features of dynamic optimization models are outlined briefly below.

As with static optimization models, an important feature of a dynamic optimization model is the function relating fitness to the organism's state at the end of a time period, called the *terminal fitness function.* Once the terminal fitness function is specified, the total time period over which choice is assessed, T, is divided into n discrete time intervals, denoted by t, during which a choice occurs. Because the optimal choice at each value of t and each state (i.e., level of energy reserves), x, depends on the outcome of future choices, optimal choices are computed backwards from $T - 1$ to $T - n$. That is, at each state, optimal choice is first computed during the final time interval, $T - 1$, by determining which choice yields the highest fitness.

Optimal choice is determined by the state dynamics proposed in a particular model. The state dynamics are the calculations that determine the expected change in state for each choice option at the current state value. The state dynamics include variables such as the mean gain, probability of gain, and cost. The fitness associated with each state at $T - 1$ is provided by the terminal fitness function. The choice option yielding the highest fitness is designated as the optimal choice. At $T - 2$, the optimal choice at each state is computed by determining which choice option yields the highest expected fitness at $T - 1$, assuming that at $T - 1$ the optimal choice occurred. These calculations are continued for each preceding time interval, producing an optimal choice matrix, sometimes called the *optimal policy*, which lists the optimal choice for each (t, x) combination (Houston & McNamara, 1988).

McNamara and Houston (1987; see also McNamara & Houston, 1992) described an optimal policy of a forager needing sufficient reserves to survive overnight. In their example, the two choice options had identical means but different variances. The terminal fitness function was assumed to be a step function, with fitness being zero if reserves were below requirements and one if reserves were above requirements. They reported that the optimal policy could be described in terms of a switching line specified by

$$x + \mu(T - t) = R, \tag{2}$$

where x is the current state, μ is the mean rate of energy gain per time interval, T is the total number of time intervals, t is the current time interval, and R is the energy requirement. In a plot of reserves versus time, risk aversion is optimal above this line and risk proneness is optimal below this line.

This model (Equation 2) is similar to the energy-budget rule (Equation 1). The primary difference between these models is that the energy-budget rule predicts only a single choice at the start of the foraging period, but the dynamic model predicts choice across the foraging period. Whether static or dynamic models are used to predict choice depends on the choice context. The static model is better suited to predict single choices, such as the choice of a food patch, whereas the dynamic model is better suited to predict sequences of choices, such as choice of food items within a patch (Bateson & Kacelnik, 1998).

Dynamic optimization models may also be used to calculate the fitness costs (i.e., loss in fitness) from choosing the nonoptimal alternative (Houston & McNamara, 1988; McNamara & Houston, 1986). This cost, called the *canonical cost,* is calculated by subtracting the expected terminal fitness value of the nonoptimal choice from the expected terminal fitness value of the optimal choice. If the optimal choice is selected, the obtained canonical cost is zero. This comparison is useful because behaving suboptimally may be more costly at some time and state values than others. McNamara and Houston argued that the canonical cost provides a common scale by which different choices, even those with different types of consequences (e.g., food or predator avoidance), can be evaluated.

Kacelnik and Bateson (1996) have noted that it is difficult to make quantitative predictions about optimal behavior from risk-sensitive foraging models. In most experiments, a number of variables are uncontrolled. For example, it is often difficult to determine energy gains and energy expenditures precisely. Furthermore, it is difficult to determine the extent to which shifts from risk aversion to risk proneness influence fitness.

One advantage of using an earnings budget instead of an energy budget is that the current state (accumulated earnings), the energy gain (reinforcer magnitude), the energy requirement (earnings requirement), and the terminal fitness function (total earnings) all can be specified and measured precisely, yielding clear quantitative predictions. In the present experiment, a dynamic optimization model was developed to predict sequences of choices within a choice period. Choices were evaluated both in relation to the predictions of this dynamic model and in relation to canonical costs.

In summary, this experiment aimed to develop a procedure with monetary outcomes to investigate risky choice in humans with manipulations that are analogous to those used in energy-budget experiments with nonhumans. Humans were given choices between a fixed and a variable number of points exchangeable for money. Choices were presented in five-trial blocks designed to simulate a daily foraging period. To model a daily energy requirement, a monetary earnings requirement was arranged for each choice period. At the end of the choice period, if the earnings requirement was met, the subject was allowed to exchange the points earned during that block for money at session's end. If the earnings requirement was not met, the earnings were lost. Meeting, or failing to meet, the earnings requirement thus produced consequences that modeled the life–death outcomes of meeting or failing to meet a daily energy requirement. If behavior is consistent with the predictions of the energy-budget model, choices should be risk averse during positive earnings-budget conditions and risk prone during negative earnings-budget conditions. Trial-by-trial choices were also measured and analyzed in relation to a dynamic optimization model.

METHOD

Subjects

The participants were 3 adult humans recruited via an advertisement in a local university newspaper. Subject 331 was a 20-year-old man, and Subjects 332 and 333 were both 22-year-old women. None had any previous experience with behavioral research.

Apparatus

Each subject was seated in a cubicle measuring 2.21 m high, 1.21 m wide, and 1.25 m deep, facing a white response panel 74 cm high and 44.5 cm wide. The upper portion (50.5 cm) of the panel was aluminum and contained three rows of 12 lights (28 V DC), with each row spaced 8 cm apart. The first and last lights of each row were white; the 10 inner lights of each row were red. Three response keys (2.5 cm diameter) were mounted 8.2 cm below the lowest row at approximately eye level and were spaced 8.2 cm apart. Each key could be transilluminated from behind by red, green, or yellow lights. A force of approximately 0.6 N was required to operate the response keys. The lower portion (23.5 cm) of the panel was constructed of wood. An opening (20 cm by 15 cm) for a television monitor (not used in the present experiment) was positioned 4 cm from the left side of the panel and 9.8 cm below the response keys. A predetermining counter (not used in the present experiment) was mounted 7 cm to the right of the monitor. A six-digit electrical counter (3 cm by 6 cm) was mounted 3 cm to the right of the predetermining counter and 13.2 cm above the bottom of the panel, and a second identical counter was mounted 1.8 cm above it.

Procedure

A session consisted of 12 blocks of five trials. The first six blocks of a session were forced-choice trials and the second six blocks were choice trials. At the start of each block, the top (trial) counter was set to zero. The start of each trial was signaled by the illumination of the center key. During choice blocks, a single response on the red center key extinguished the keylight and illuminated both side keys. The fixed and variable alternatives were correlated with yellow and green keylights, respectively, which flashed according to a 0.25-s on-off cycle. The key positions of the fixed and variable options were randomly determined on each trial. Five responses on one of the keys extinguished both keylights and produced points. If the fixed option was selected, 2 points were added to the trial counter; if the variable option was selected, 1 or 3 points ($p = .5$) were added to the trial counter. Each point addition to the trial and block counter was accompanied by a brief (0.2-s) tone. When the number of points on the trial counter equaled the point requirement, the six white lights on the upper portion of the panel were illuminated. If the number of points on the trial counter equaled or exceeded the point requirement following point delivery on the fifth trial of a block, the points on the trial counter were added to the lower (block) counter and the six white lights were extinguished. If the number of points on the trial counter was less than the point requirement, no points were added to the block counter and the trial

Table 1

Sequence and number of sessions per condition (in parentheses) for each subject.

Earnings-budget condition	Subject		
	331	332	333
Positive (R = 10)	1 (10) 3 (19)	1 (7) 3 (12)	1 (9) 3 (16) 5 (6)
Negative (R = 12)	2 (8)	2 (6)	
Negative (R = 13)	4 (5)	4 (5)	2 (10) 4 (7)

counter was reset to zero. Each trial was separated by a 30-s intertrial interval (ITI).

Forced-choice blocks were similar to choice blocks except that only one keylight was illuminated and across all five trials only the fixed or variable option was presented. The schedule type was randomly determined in each block, with the restriction that three blocks presented only the fixed option and three blocks presented only the variable option. Across forced-choice and choice trials, pressing a dark key or switching between keys reset the fixed-ratio 5 schedule, such that five consecutive responses were required to produce points.

The point requirement was manipulated across conditions. During positive earnings-budget conditions, the point requirement was 10 points (R = 10). Under these conditions, exclusive preference for the fixed option would meet the requirement; exclusive preference for the variable option would meet the requirement half the time, on average. During negative earnings-budget conditions, the point requirement was either 12 points (R = 12) or 13 points (R = 13). Exclusive preference for the fixed option would not meet the requirement under either of these conditions; exclusive preference for the variable option would occasionally meet the criterion (.19 probability during both the R = 12 and R = 13 conditions).

Table 1 shows the sequence and number of sessions per condition for each subject. Conditions were changed after a minimum of five sessions and when the number of choices for the fixed option was stable across three consecutive sessions, as determined by visual inspection. Sessions were conducted at approximately the same time, Monday through Friday. Typically, two sessions were conducted daily, separated by a brief (approximately 2-min) break.

All subjects were exposed to positive earnings-budget conditions (R = 10) before the negative earnings-budget conditions (R = 12, R = 13). Because Subject 333 showed little sensitivity to earnings-budget contingencies during the initial exposures to these conditions, the number of forced-choice blocks per session was increased from 6 to 10 during the replication of the positive earnings-budget (R = 10) conditions. The number of forced-choice blocks was gradually reduced across sessions until it reached the terminal value of six, where it remained for the rest of the experiment.

The following instructions were posted to the right of the response panel and were read to the subject prior to the first experimental session:

> You may earn points by pressing the response keys when lit. Press only one key at a time. Each point displayed on the lower, right counter is worth 2.5¢. Please remain seated. You will be informed when the session is over.

Point earnings were exchanged for cash immediately following each session. Subjects were also given a receipt after each session in the amount of $1.50. At the end of the experiment, a check for the sum of these receipts was mailed to the subject. Overall earnings averaged about $6.70 per hour.

RESULTS

Across-Block Choices

Figure 1 shows the number of choices for the fixed option and point earnings during

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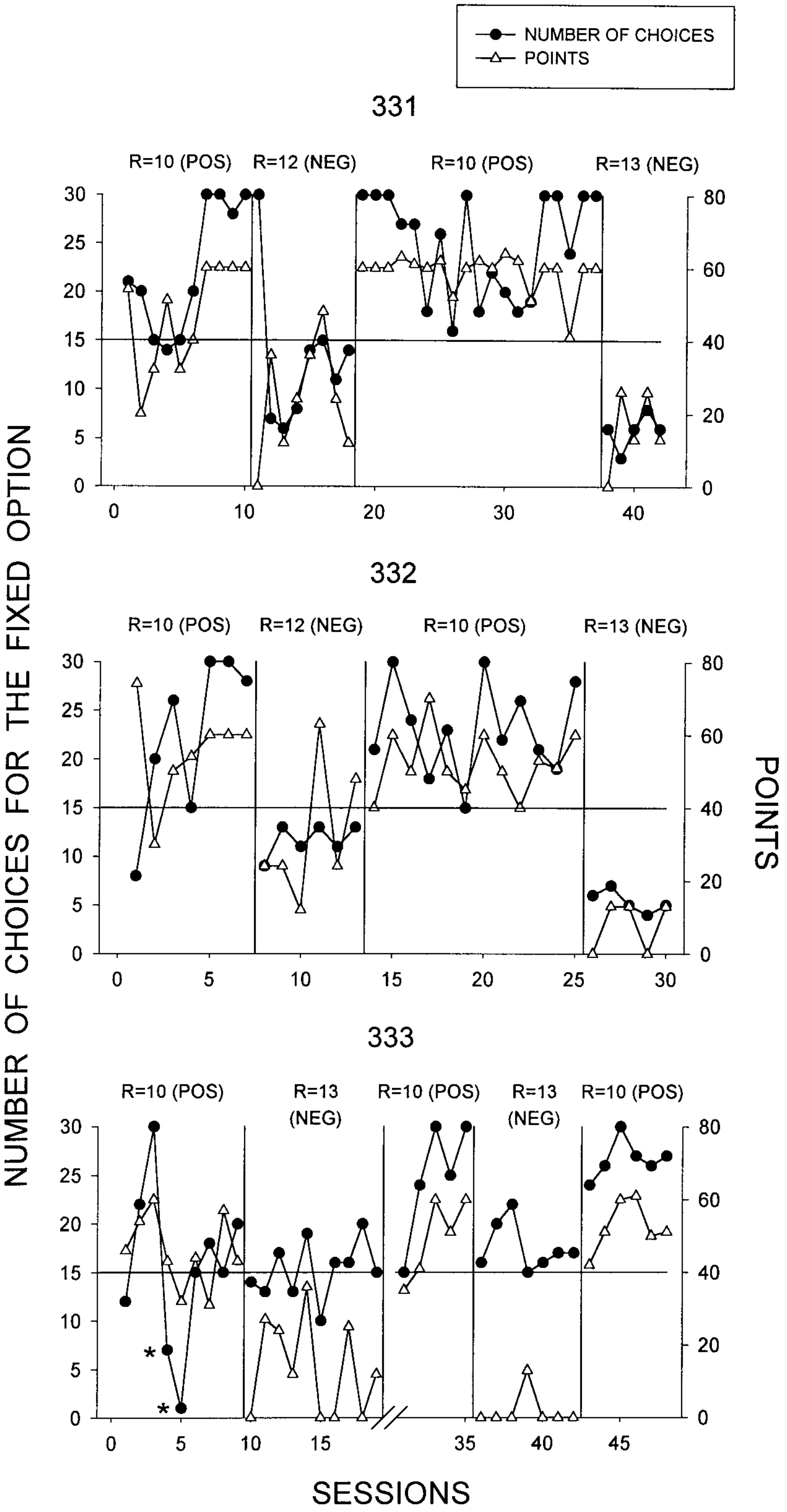
Fig. 1. Number of choices for the fixed option (filled circles) and point earnings per session (open triangles) across positive (POS) and negative (NEG) earnings-budget conditions for each subject. The horizontal line indicates indifference between the two options. The two asterisks on the graph for Subject 333 indicate sessions in which the trial counter was inoperative due to a mechanical failure. Sessions conducted with additional forced-choice trials for Subject 333 have been omitted.


NUMBER OF CHOICES
POINTS
331
R=10 (POS)
R=12 (NEG)
R=10 (POS)
R=13 (NEG)
332
R=10 (POS)
R=12 (NEG)
R=10 (POS)
R=13 (NEG)
333
R=10 (POS)
R=13 (NEG)
R=10 (POS)
R=13 (NEG)
R=10 (POS)
*
*
NUMBER OF CHOICES FOR THE FIXED OPTION
POINTS
SESSIONS
0
5
10
15
20
25
30
35
40
45
80
60
40
20

choice trials across conditions. The horizontal line indicates the indifference point between the two options. Choice was defined as risk averse if the number of choices for the fixed option was above the line and as risk prone if the number of choices was below it. For Subject 333, sessions conducted with additional forced-choice trials have been omitted (denoted by a break in the *x* axis). For each subject, the across-block choices showed sensitivity to earnings-budget conditions. Subjects 331 and 332 preferred the fixed option (risk aversion) during both exposures to positive earnings-budget conditions ($R = 10$) and the variable option (risk proneness) during negative earnings-budget conditions ($R = 12$, $R = 13$). The mean number of fixed choices decreased approximately 50% as the requirement was increased from 12 to 13. Session-to-session choices tended to be more variable during positive than negative earnings-budget conditions for both subjects, particularly during the second exposure to positive earnings-budget ($R = 10$) conditions.

For Subjects 331 and 332, during the first exposure to positive earnings-budget conditions, clear preferences for the fixed option developed in seven and five sessions, respectively. In subsequent conditions, preferences shifted rapidly with changes in earnings-budget conditions, typically in the first session. Such rapid transitions were likely due to the 30 forced-choice trials at the beginning of each session.

Choice patterns of Subject 333 were also sensitive to positive and negative earnings-budget conditions, but the sensitivity was weaker than for the other 2 subjects. During the first exposure to both the positive earnings-budget ($R = 10$) condition and the negative earnings-budget ($R = 13$) condition, the number of choices for the fixed option was similar. Temporarily increasing exposure to the contingencies increased preference for the fixed option to levels comparable to the other 2 subjects. The number of choices for the fixed option decreased markedly during the negative earnings-budget ($R = 13$) condition, although a slight preference for the fixed option prevailed. As with Subjects 331 and 332, across the final three conditions, preferences shifted in the first session following a transition to a new earnings-budget condition.

Point earnings varied substantially across positive and negative earnings-budget conditions. Earnings were generally high during positive earnings-budget ($R = 10$) conditions, considerably lower during negative earnings-budget conditions ($R = 12$), and lower still under the most stringent negative earnings-budget conditions ($R = 13$).

Within-Block Choices

Figures 2, 3, and 4 show for each subject the number of fixed choices and variable choices per trial as a function of the number of accumulated points during the final three sessions of each condition. Because each session consisted of six choice blocks, the total number of choices at each trial position was 18. Bars to the left of the vertical line in each graph represent choices that occurred when the point earnings were insufficient to meet the point requirement no matter what the choice. Asterisks indicate optimal choices (see below). For Subject 333, within-block choices are presented only for the final three earnings-budget conditions.

During positive earnings-budget conditions, few variable choices occurred and the number of fixed choices was generally consistent across trials within a block. During negative earnings-budget conditions, the number of fixed choices tended to shift across trials within a block for Subjects 331 and 332. These shifts in preference were due primarily to choices that occurred when the number of accumulated points was insufficient to meet the point requirement. When that happened, Subject 331 showed a near equal preference for the fixed and variable options, and Subject 332 showed a strong preference for the variable option. Because point earnings became insufficient later in the block, particularly during the negative earnings-budget ($R = 13$) conditions, these preferences produced an increase in the number of fixed choices across the block for Subject 331 and a decrease for Subject 332. For Subject 333, the number of fixed and variable choices remained about the same across the block during negative earnings-budget conditions, and when the number of accumulated points was insufficient to meet the requirement, neither the fixed or variable option was strongly preferred.

If enough points were earned during neg-

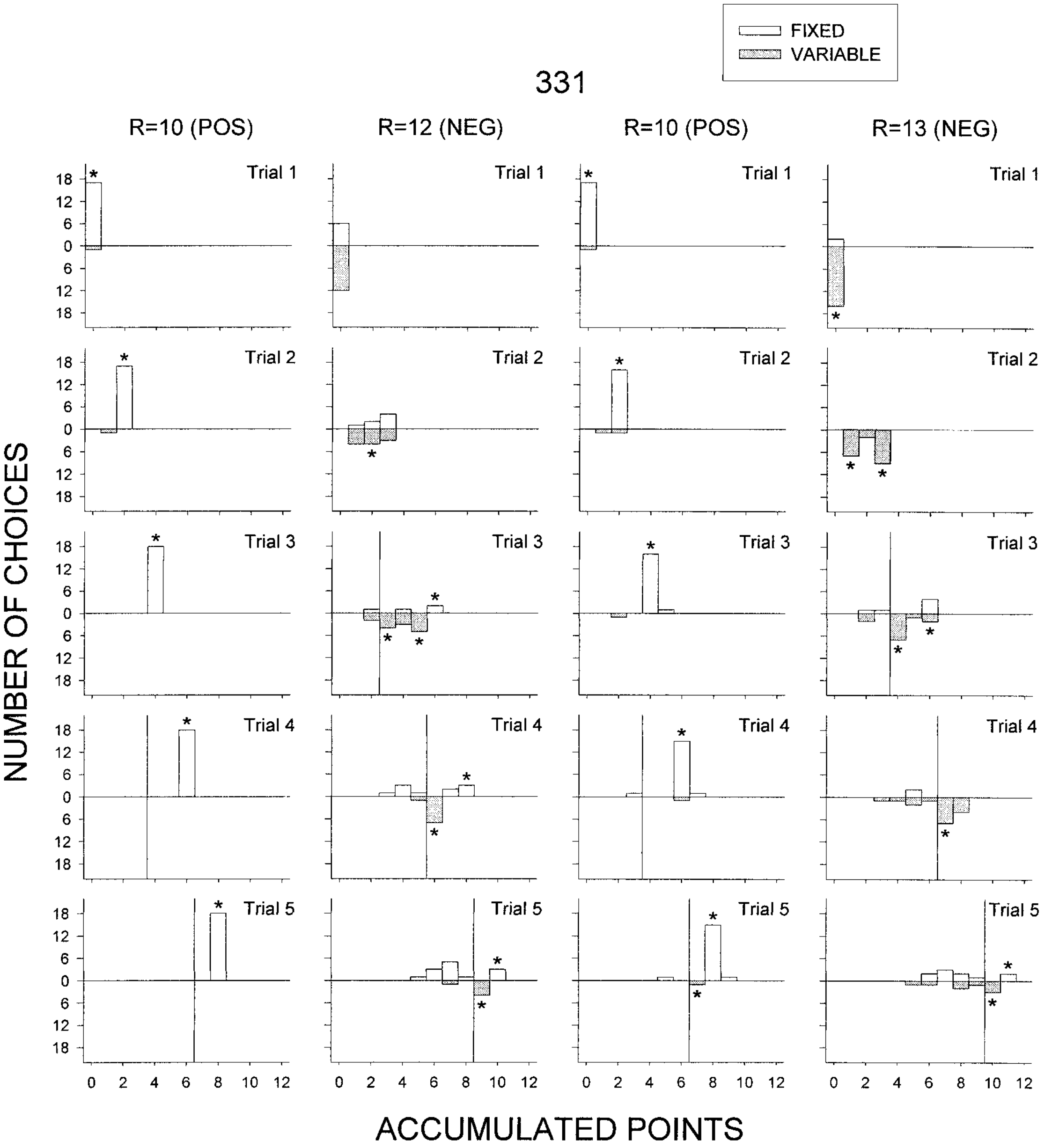


Fig. 2. Number of choices for the fixed option and variable option per trial as a function of the number of accumulated points for Subject 331. Choices are from the final three sessions of each condition. Open bars above the *x* axis show the number of choices for the fixed option, and filled bars below the *x* axis show the number of choices for the variable option. Bars to the left of the vertical line in each graph represent choices that occurred when the point earnings were below the minimum amount needed to meet the point requirement. Asterisks show the optimal choices for specific trial and point combinations.

ative earnings-budget conditions, selecting the fixed option could meet the earnings requirement. The relation between choice and earnings is shown in Figure 5. Lines labeled A and B show that when the requirement was 12 or 13 points, if a sufficient number of points was accumulated, then switching from the variable option and persisting with the fixed option could meet the point requirement (e.g., if 6 points had been accumulated

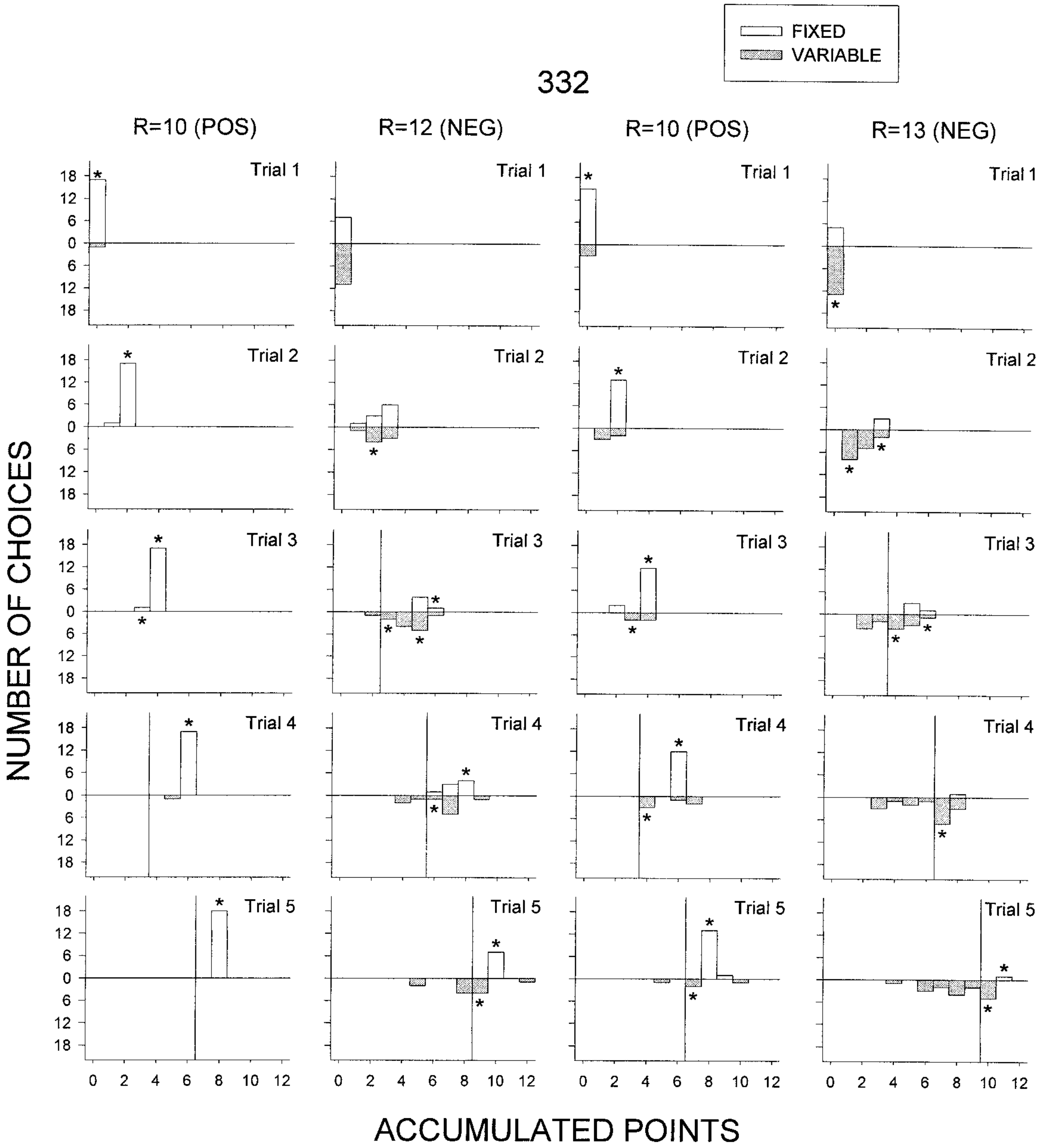


Fig. 3. Number of choices for the fixed option and variable option per trial as a function of the number of accumulated points for Subject 332. Details are as in Figure 2.

by the start of Trial 3 when the point requirement was 12). Subjects 331 and 332 frequently selected the fixed option during negative earnings-budget conditions at these trial and point combinations: The fixed option was selected on 100% (331) and 93% (332) of such trials (see Figures 2 and 3). For Subject 333, during the final three sessions of the negative earnings-budget ($R = 13$) condition, no trials occurred in which switching to the fixed option could meet the requirement.

To examine within-block choices in greater quantitative detail, performance was analyzed in accordance with the predictions of a dynamic optimization model. The model generated expected earnings for fixed and vari-

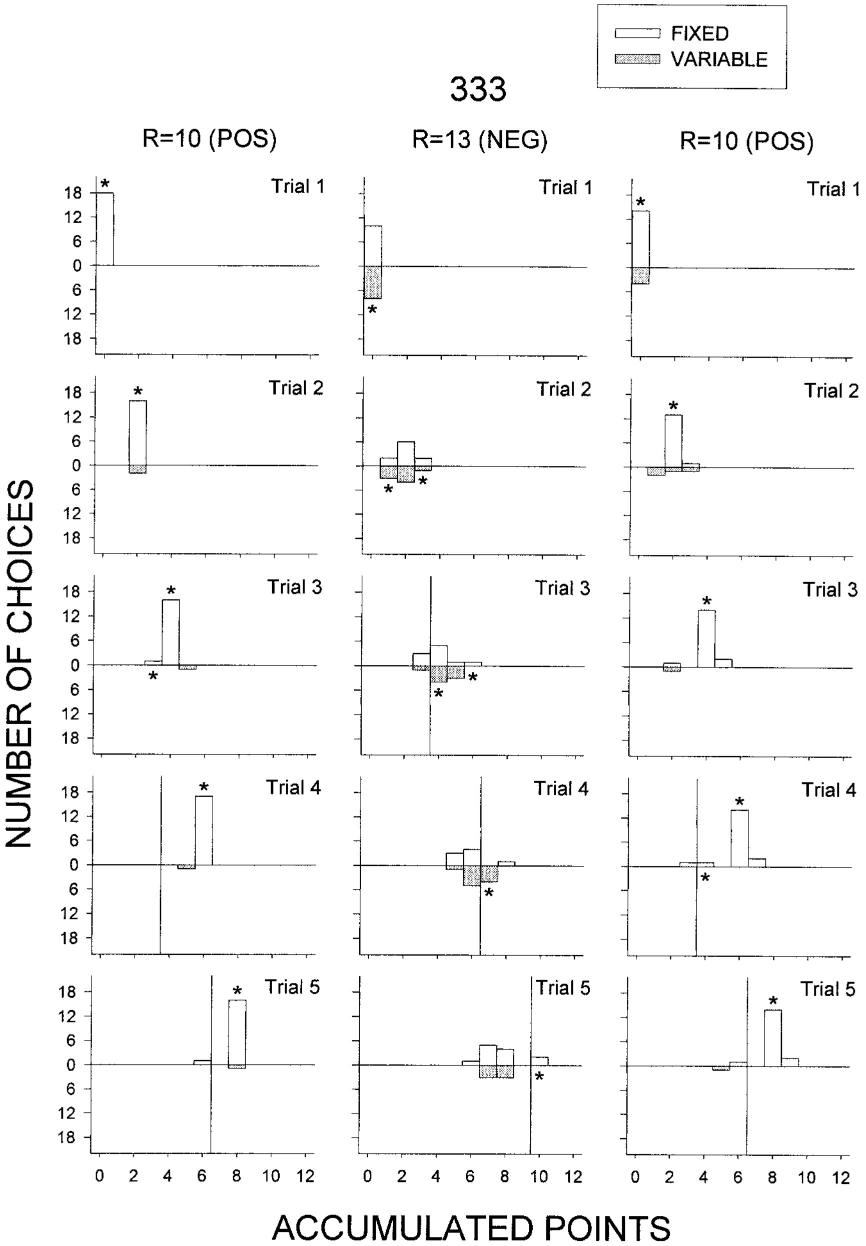


Fig. 4. Number of choices for the fixed option and variable option per trial as a function of the number of accumulated points for Subject 333. Only choices from the final three earnings-budget conditions are shown. Details are as in Figure 2.

able choices at each number of accumulated points for each trial of a block. The choice sequence yielding the highest expected earnings was designated as the optimal choice. A description of how the model generated expected earnings, and thus optimal choices, is presented in the Appendix.

Optimal choices at specific trial and point combinations are indicated by asterisks in Figures 2, 3, and 4. Asterisks above the *x* axis indicate that choices for the fixed option were optimal, and asterisks below the *x* axis indicate that choices for the variable option were optimal. Trial and point combinations

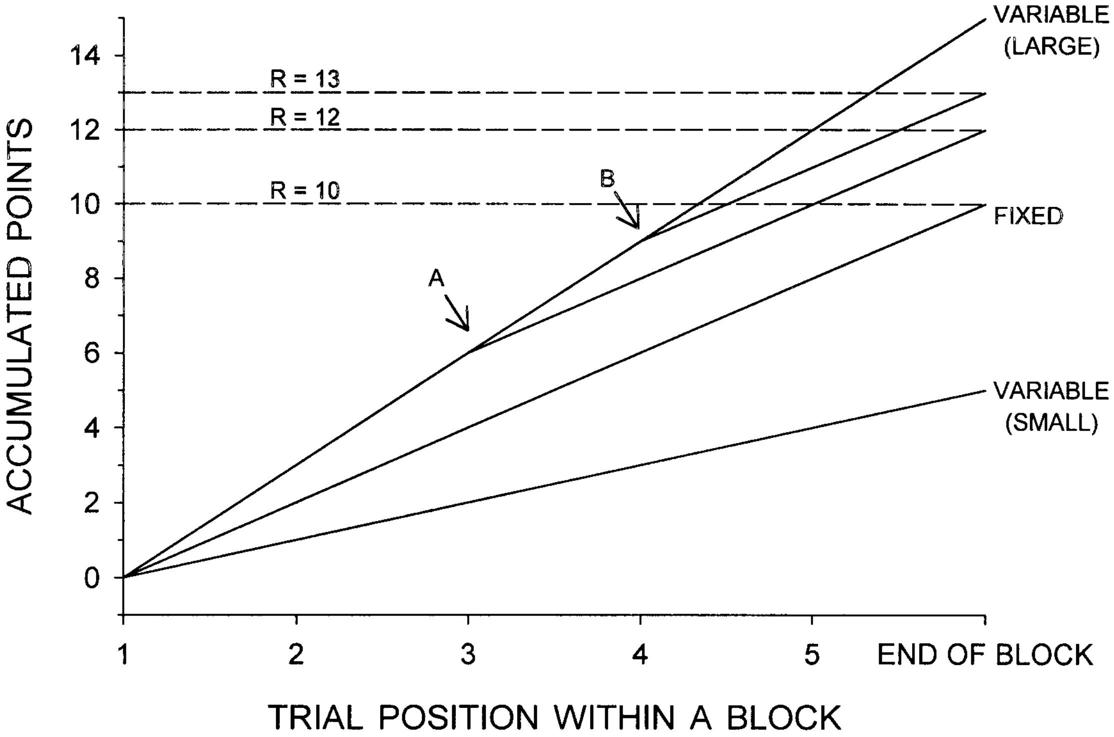


Fig. 5. Range of potential point earnings across five-trial blocks. Lines labeled "variable (large)" and "variable (small)" show the point earnings if the variable option was selected on every trial and every choice produced the large (3 points) and small amounts (1 point), respectively. The line labeled "fixed" shows the point earnings if the fixed option was selected on every trial (2 points). The area between the variable (large) and variable (small) lines is the range of potential earnings. The three horizontal lines show the earnings requirement, R, during the positive earnings-budget (R = 10), negative earnings-budget (R = 12), and negative earnings-budget (R = 13) conditions. Lines labeled A and B show that selections of the fixed option could meet the earnings requirement under negative earnings-budget (R = 12) and (R = 13) conditions, respectively, if a sufficient number of points was accumulated.

without an asterisk indicate that neither a choice for the fixed or variable option was predicted.

Choices were generally consistent with the model's predictions, particularly for the 2 subjects (Subjects 331 and 332) whose choices were most sensitive to the earnings-budget contingencies. For these 2 subjects, within-block choices were similar. Choices tended to be more consistent with predictions during positive earnings-budget conditions than during negative earnings-budget conditions. The total proportions of choices consistent with predictions during the final three sessions of positive and negative earnings-budget conditions, respectively, were .98 and .81 for Subject 331 and .93 and .79 for Subject 332. In all conditions, choices became more consistent with the predictions of the model across trials within a block. That is, choices were more likely to deviate from the optimal pattern earlier than later in a block. In positive earnings-budget conditions, most deviations were the result of choices for the variable option early in the block when preference for the fixed option was predicted. In negative earnings-budget conditions, most deviations were the result of choices for the fixed option early in the block when preference for the variable option was predicted.

For Subject 333, within-block choices were generally consistent with predictions during positive earnings-budget conditions, but were often inconsistent with predictions during the negative earnings-budget condition. The total proportions of choices consistent with predictions during the final three sessions of positive and negative earnings-budget conditions were .97 and .48, respectively. Choices showed only a slight tendency to become more consistent with predictions across trials within a block.

For each subject, within-block choices were evaluated in relation to canonical cost by plotting the proportion of choices consistent with predictions as a function of the canonical costs (i.e., losses in earnings) of nonoptimal choices. These results are shown in Figure 6. (A description of how canonical costs were determined is presented in the Appendix.) Proportions were calculated for each trial and point combinations for which a fixed or variable choice was predicted (trial and point combinations marked with asterisks in Figures 2, 3, and 4). Overall, choices of Subjects 331 and 332 were more consistent with predictions at higher than at lower canonical costs. This trend was less apparent for Subject 333, whose choices showed little relation to canonical cost.

DISCUSSION

Choice patterns in all subjects were sensitive to earnings-budget manipulations. For the 2 subjects who showed the greatest sensitivity (Subjects 331 and 332), preference for the fixed option (risk aversion) under positive earnings-budget conditions switched to preference for the variable option (risk proneness) under negative earnings-budget conditions. Choice was more risk prone during the negative earnings-budget (R = 13) condition, in which the point requirement was more stringent, than during the negative earnings-budget (R = 12) condition. For Subject 333, choice was risk averse during two of the three exposures to the positive earnings-budget (R = 10) condition. Although choice remained slightly risk averse during the negative earnings-budget (R = 13) conditions, the number of choices for the fixed option was considerably lower than during the positive earnings-budget (R = 10) conditions. Thus, choices shifted in the same direction as for the other 2 subjects. Choices for Subject 333 were therefore qualitatively consistent, whereas choices for Subjects 331 and 332 were quantitatively consistent, with the predictions of the energy-budget model.

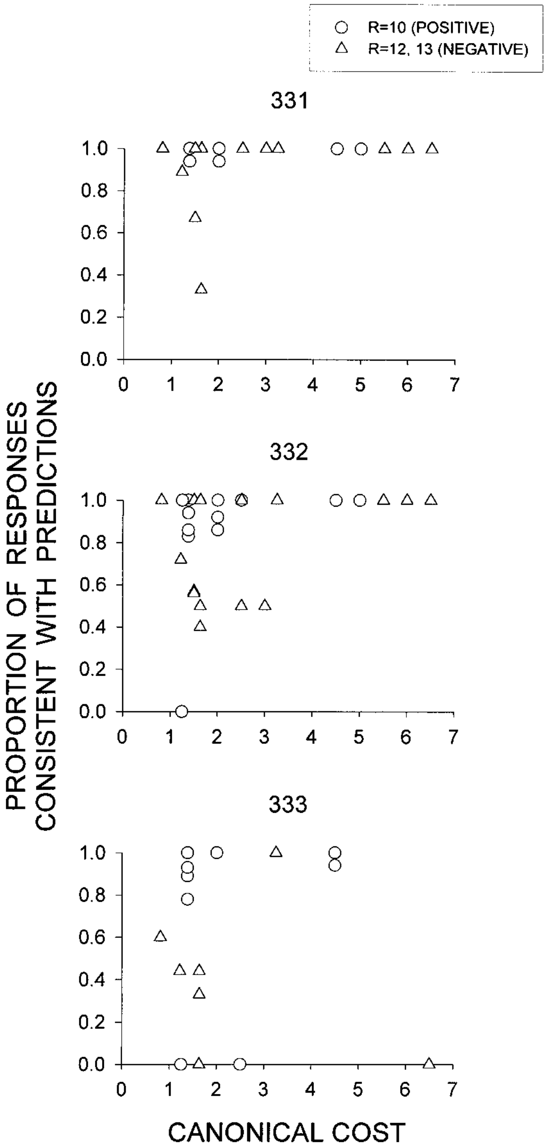


Fig. 6. Proportion of within-block choices that were consistent with the predictions of an optimization model plotted as a function of the canonical cost of selecting the nonoptimal alternative. Proportions were calculated across the final three sessions of each earnings-budget condition for each subject. Circles show proportions from positive earnings-budget conditions, and triangles show proportions from negative earnings-budget conditions.

As shown in Figure 5, switching from the variable to the fixed option when a sufficient number of points had been accumulated under negative earnings-budget conditions could meet the point requirement. Subjects 331 and 332 typically switched on these occasions. This pattern of switching produced point totals that approached the maximum potential earnings. During both negative earnings-budget conditions, exclusive preference for the variable option would meet the requirement with $p = .19$, and thus produce an average of 15 points per session. (The probability of meeting the requirement was identical under $R = 12$ and $R = 13$ conditions because in both, four 3-point outcomes were needed to meet the point requirement.) Switching, however, would increase the probability of meeting the point requirement to .38 (producing 27 points, on average) and to .22 (producing 17 points, on average) for $R = 12$ and $R = 13$, respectively. Because Subjects 331 and 332 frequently switched during negative earnings-budget conditions when a sufficient number of points was accumulated, obtained point earnings per session were often closer to these levels than to those that would result from exclusive preference for the variable option (Figure 1).

That switching between alternatives yielded higher point earnings than exclusive preference parallels suggestions made by behavioral ecologists that switching between fixed and variable options can increase fitness (e.g., Houston & McNamara, 1982). The present within-block choice patterns also agree with the results of previous studies with humans showing that choices often maximize overall reinforcement rates with point–money consequences like those used here (e.g., Jacobs & Hackenberg, 1996; Logue, Peña-Correal, Rodriguez, & Kabela, 1986).

The dynamic optimization model specified optimal choices at many trial and point combinations during both positive and negative earnings-budget conditions (as well as predicting the pattern of switching during negative earnings-budget conditions described above). Within-block choices were usually consistent with the predictions of the model, particularly for Subjects 331 and 332, indicating that choices were optimal not only at the global level but also at the more local level of individual choices. Because the predictions of the model were determined by the number of accumulated points, the number of points produced by fixed and variable choices, the position within the block, and the point requirement, these results show that choices for these 2 subjects were simultaneously sensitive to all of these variables. In behavior-analytic terms, the point-requirement contingency reinforced particular choice sequences and established both the number of accumulated points and stimuli correlated with trial position as discriminative stimuli for within-block choices. Within-block choices (Figures 2, 3, and 4) also showed that across-block choice patterns in positive and negative earnings-budget conditions were not the result of some general preference for fixed or variable alternatives, but were the result of specific trial-by-trial choices.

Although choices occasionally deviated from the predictions of the optimization model for Subjects 331 and 332, Figure 6 showed that the deviations were systematically related to the canonical cost. When deviating from the optimal pattern was not costly (i.e., early in the block), the proportion of choices consistent with predictions was lower than when deviating from the optimal pattern was costly (i.e., later in the block). These results thus suggest that within-block choice patterns were sensitive to the differential (point) consequences of selecting the fixed and variable options.

The present results parallel those shown in energy-budget research with nonhumans (e.g., Barnard & Brown, 1985; Caraco et al., 1980). Of particular relevance to the present study are the results of an experiment by Caraco et al. (1990). In this study, choice was risk averse when energy requirements were low (positive energy-budget conditions) but was risk prone when energy requirements were high (negative energy-budget conditions). Similarly, in the present study choice was risk averse when the point requirement was low (positive earnings-budget conditions) and was more risk prone when the point requirement was high (negative earnings-budget conditions). Additional research is required to determine whether the same shifts in risk sensitivity can be produced in humans by the more common methods of changing energy budget, for example, by changing the rate of reinforcement (i.e., changing the point earnings on the fixed and variable option) or the earnings reserves (i.e., changing points available at the start of each block).

Energy-budget models, including the energy-budget rule, assume that foraging choices are shaped by natural selection. They do not make any assumptions about the behavioral mechanisms or proximate variables underlying those choices (Bateson & Kacelnik, 1998). Because there are many important differences between the present procedure and typical energy-budget procedures, it is possible that the variables that govern risky choice in relation to earnings budgets differ from those that govern risky choice in relation to energy budgets.

That energy budgets and earnings budgets have similar effects on choice, however, suggests that the patterns of risk sensitivity generated by the gains from fixed and variable choices, current state, temporal constraints, and requirements extend beyond situations that involve biologically important consequences. Although they are based on assumptions about the fitness consequences of risk-averse and risk-prone choices for foraging animals, the predictions of the energy-budget model generalize to a broad range of contexts, including humans choosing between monetary reinforcers. Thus, energy-budget conditions may be viewed as a special case of a more general set of relations involving interactions between contingencies arranged for individual choices and contingencies arranged for aggregate choices.

Although we have emphasized research and models developed by behavioral ecologists, the present results are also relevant to more cognitively oriented models that have been developed by researchers in the area of judgment and decision making. Of particular note is the common finding that risky choice in humans is influenced by the probability that a choice outcome will fall above or below a particular monetary value (e.g., Payne, Laughhunn, & Crum, 1980; Tversky & Kahneman, 1981). This value, called variously a target, reference point, or aspiration level, is used to explain the well-documented finding of risk aversion when choice outcomes are gains and risk proneness when outcomes are losses (Kahneman & Tversky, 1979).

Caraco and Lima (1987) suggested that the shift from risk aversion to risk proneness shown in nonhumans across positive and negative energy budgets is similar to the shift from risk aversion to risk proneness shown in humans across monetary gains and losses. As noted by Luce (1996), however, researchers lack suitable methods for estimating targets in individual subjects. The present procedure eliminates this problem by establishing targets within the experimental setting. Furthermore, because the present procedures combined the monetary outcomes typical of experiments on human decision making with energy-budget manipulations typical of optimal foraging research, they help to establish a more direct link between models developed by psychologists and models developed by behavioral ecologists.

To date, there have been few attempts to integrate risky-choice research conducted by psychologists and behavioral ecologists into a single conceptual framework. A major obstacle to the development of an interdisciplinary approach to risky choice is the vastly different methods employed by researchers in different traditions. Developing a common set of procedures that can be adopted by researchers from different disciplines may promote the development of models and interpretations of risky choice that apply across a variety of species and choice contexts.

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APPENDIX

To illustrate how the predictions of the dynamic optimization model were generated, it will be useful to work through an example that parallels one provided by Houston and McNamara (1988). Consider a choice during the fifth (final) trial of a block ($T - 1$) if 8 points have been accumulated ($x = 8$) and the requirement, R, was 10 points. In the present experiment, the terminal fitness function, designated $R(x)$, was defined as

$$R(x) = \begin{cases} 0 & \text{if } x < R \\ x & \text{if } x \geq R. \end{cases}$$

Selections of the fixed option produce 2 points, and selections of the variable option produce either 1 or 3 points ($p = .5$). If the variable option is selected, the final value of x will be either 9 or 11 with equal probability. If the fixed option is selected, the final value of x will be 10 with certainty. Thus, the expected earnings, E, at state x, given a fixed (F) or variable (V) choice, at time $T - 1$ may be calculated as

$$\begin{aligned} E(8, F, T-1) &= [1 \cdot R(10)] = (1 \cdot 10) = 10 \\ E(8, V, T-1) &= [.5 \cdot R(9)] + [.5 \cdot R(11)] \\ &= (.5 \cdot 0) + (.5 \cdot 11) = 5.5. \end{aligned}$$

Thus, the optimal choice is the fixed option. However, if 7 points had been accumulated at $T - 1$, then

$$\begin{aligned} E(7, F, T-1) &= [1 \cdot R(9)] = (1 \cdot 0) = 0 \\ E(7, V, T-1) &= [.5 \cdot R(8)] + [.5 \cdot R(10)] \\ &= (.5 \cdot 0) + (.5 \cdot 10) = 5, \end{aligned}$$

in which case the optimal choice is the variable option. To predict choice during the fourth trial of a block ($T - 2$), the values of the terminal fitness function, $R(x)$, are replaced with the expected earnings at each state at $T - 1$, designated $\psi(x)$, given that the optimal choice occurred. For example, because choice of the fixed option was optimal at $x = 8$ and $T - 1$, $\psi(8)$ at $T - 2$ will equal 10. If 6 points had been accumulated ($x = 6$) at $T - 2$,

$$\begin{aligned} E(6, F, T-2) &= [1 \cdot \psi(8, T-1)] = (1 \cdot 10) \\ &= 10 \\ E(6, V, T-2) &= [.5 \cdot \psi(7, T-1)] \\ &\quad + [.5 \cdot \psi(9, T-1)] \\ &= (.5 \cdot 5) + (.5 \cdot 11) = 8. \end{aligned}$$

Therefore, the optimal choice is the fixed option. At each time and state, the expected earnings are thus the average number of points that will be accumulated at the end of the block, given that the optimal choice is selected on each remaining trial.

Tables 2, 3, and 4 show the expected earnings associated with selecting the fixed and variable option at each number of accumulated points during each trial of a block for the positive earnings-budget ($R = 10$), negative earnings-budget ($R = 12$), and negative earnings-budget ($R = 13$) conditions, respectively. The optimal choice at each trial within a block is underlined. The final column in each table shows the values of the terminal fitness (i.e., total earnings) function, $R(x)$. As described above, the terminal fitness function specified that the number of points earned at the end of a block would equal zero if the number of accumulated points was below the requirement, and would equal the point earnings if the number of accumulated points was equal to or greater than the requirement. The maximum value of $R(x)$ was 15—the maximum number of points that could be earned per block. Overall, the tables show that preference for the risky option was predicted only when the expected earnings were below the requirement. Preference for the fixed option was predicted when the expected earnings equaled the requirement. When the expected earnings of the fixed and variable option were identical, no particular choice was designated as optimal.

Also included in Tables 2, 3, and 4 are the canonical costs, or losses in expected point earnings from selecting the nonoptimal alternative. These values were calculated by subtracting the expected earnings of nonoptimal choices from the expected earnings of optimal choices. If choice was sensitive to the differential costs of choosing optimal and nonoptimal alternatives, then deviations from the optimal pattern should vary inversely with the cost of such deviations.

Table 2

Expected point earnings for selections of the fixed (F) and variable (V) option at each number of accumulated points for the positive earnings-budget ($R = 10$) condition. The optimal choice is underlined. $R(x)$ indicates the terminal fitness function (the number of points delivered for each number of accumulated points following the fifth trial). Also shown is the canonical cost (loss in point earnings) of selecting the nonoptimal choice.

	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
Points	F	V	Cost	F	V	Cost	F	V	Cost	F	F	Cost	F	V	Cost	$R(x)$
0	10	8.63	1.37													0
1				6.25	6.25											0
2				10	8.63	1.37	2.5	2.5								0
3				11	11		5	6.25	1.25	0	0					0
4							10	8	2	0	2.5	2.5	0	0		0
5							11	11		5	5		0	0		0
6							12	12		10	8	2	0	0		0
7										11	11		0	5	5	0
8										12	12		10	5.5	4.5	0
9										13	13		11	11		0
10													12	12		10
11													13	13		11
12													14	14		12
13																13
14																14
15																15

Table 3

Expected point earnings, canonical costs, and terminal fitness function, $R(x)$, for the negative earnings-budget ($R = 12$) condition. All other details as in Table 2.

	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
Points	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	$R(x)$
0	4.5	4.5														0
1				1.5	1.5											0
2				3	4.5	1.5	0	0								0
3				7.5	7.5		0	1.5	1.5	0	0					0
4							3	3		0	0		0	0		0
5							6	7.5	1.5	0	0		0	0		0
6							12	9.5	2.5	0	3	3	0	0		0
7										6	6		0	0		0
8										12	9.5	2.5	0	0		0
9										13	13		0	6	6	0
10													12	6.5	5.5	0
11													13	13		0
12													14	14		12
13																13
14																14
15																15

Table 4

Expected point earnings, canonical costs, and terminal fitness function, $R(x)$, for the negative earnings-budget ($R = 13$) condition. All other details as in Table 2.

	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
Points	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	$R(x)$
0	1.63	$\underline{2.84}$	1.21													0
1				0	$\underline{0.81}$	0.81										0
2				1.63	1.63		0	0								0
3				3.25	$\underline{4.88}$	1.63	0	0		0	0					0
4							0	$\underline{1.63}$	1.63	0	0		0	0		0
5							3.25	3.25		0	0		0	0		0
6							6.5	$\underline{8.13}$	1.63	0	0		0	0		0
7										0	$\underline{3.25}$	3.25	0	0		0
8										6.5	6.5		0	0		0
9										$\underline{13}$	10.25	2.75	0	0		0
10													0	$\underline{6.5}$	6.5	0
11													$\underline{13}$	7	6	0
12													14	14		0
13																13
14																14
15																15