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HUMAN RISKY CHOICE UNDER TEMPORAL CONSTRAINTS: TESTS OF AN ENERGY-BUDGET MODEL

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Risk-sensitive foraging models predict that choice between fixed and variable food delays should be influenced by an organism's energy budget. To investigate whether the predictions of these models could be extended to choice in humans, risk sensitivity in 4 adults was investigated under laboratory conditions designed to model positive and negative energy budgets. Subjects chose between fixed and variable trial durations with the same mean value. An energy requirement was modeled by requiring that five trials be completed within a limited time period for points delivered at the end of the period (block of trials) to be exchanged later for money. Manipulating the duration of this time period generated positive and negative earnings budgets (or, alternatively, ''time budgets''). Choices were consistent with the predictions of energy-budget models: The fixed-delay option was strongly preferred under positive earnings-budget conditions and the variable-delay option was strongly preferred under negative earnings-budget conditions. Within-block (or trial-by-trial) choices were also frequently consistent with the predictions of a dynamic optimization model, indicating that choice was simultaneously sensitive to the temporal requirements, delays associated with fixed and variable choices on the upcoming trial, cumulative delays within the block of trials, and trial position within a block.

Key words: risky choice, energy budget, optimal foraging theory, monetary outcomes, adult humans

Choice in situations of uncertainty or risk has been approached from several traditions of research and theory including psychology, behavioral ecology, anthropology, and economics. The term *risk* is usually invoked to describe choices in relation to variably-distributed outcomes. Choice is said to be *risk averse* if a fixed (i.e., constant) or low-variance resource is preferred to a more variable alternative and *risk prone* if the more variable outcome is preferred to the fixed or less variable outcome (Bateson & Kacelnik, 1998; Stephens & Krebs, 1986).

One approach to the problem comes from optimal foraging theory. Classical optimal foraging models assume that animals' food-related choices are governed solely by overall mean rate of energy gain, but several models have been developed over the past 20 years to describe risk-sensitive foraging in situations involving variability in amount of, and delay to, food (e.g., Caraco, 1980; McNamara & Houston, 1987, 1992; Real, 1980; Stephens, 1981). One class of models predicts that risk sensitivity should be influenced by a forager's energy budget (Stephens & Krebs, 1986). An energy budget is defined as the relation between an organism's energy reserves and energy requirements (Bateson & Kacelnik, 1998). When rates of energy gain and/or current energy reserves are sufficient to meet the energy requirements, the energy budget is positive. Conversely, if the energy gain and/or current energy reserves are insufficient to meet the energy requirements, the energy budget is negative.

One of the most extensively studied energy-budget models is known as the z-score model or, alternatively, the energy-budget rule (Stephens, 1981; Stephens & Krebs, 1986). The energy-budget rule was designed to predict choices between fixed and variable (or low and high variance) food amounts under conditions in which an animal requires sufficient energy reserves to survive overnight (although the model may also be extended to other time periods). The principal assumption of the energy-budget rule is that a forager's choices will minimize the probability of an energy shortfall (starvation). According to the energy-budget rule, when the fixed and

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variable options have the same mean value, the probability of starvation can be minimized by selecting the fixed option when the energy budget is positive and selecting the variable option when the energy budget is negative (for a formal presentation of the model's predictions, see Caraco & Lima, 1987; Stephens; Stephens & Krebs). Risk proneness is predicted when the energy budget is negative because only the variable option can yield sufficient energy returns to meet the energy requirement.

Studies using a variety of nonhuman species have shown that choice between fixed and variable amounts of food is often consistent with the predictions of the energy-budget rule, including studies with mammals (Barnard & Brown, 1985), birds (Caraco, 1981; 1983; Caraco et al., 1990; Caraco, Martindale, & Whittam, 1980), fish (Croy & Hughes, 1991; Young, Clayton, & Barnard, 1990), and insects (Cartar, 1991; Cartar & Dill, 1990; for reviews see Bateson & Kacelnik, 1998; Kacelnik & Bateson, 1996; Real & Caraco, 1986). Many studies conducted by anthropologists, behavioral ecologists (e.g., Cashdan, 1990), and psychologists (e.g., Kahneman & Tversky, 1979) have shown that human choice is also risk sensitive, but relatively little is known about the effects of energy-budget variables in humans.

Although some field studies with humans are broadly consistent with the energy-budget rule (Kunreuther & Wright, 1979; see also Winterhalder, Lu, & Tucker, 1999), they lack the quantitative rigor needed for strong tests of the model. That is, outside the laboratory it is difficult to manipulate and assess variables that determine energy budget and it is often not feasible to eliminate extraneous variables. Recently, investigators have evaluated human risky choice under laboratory conditions designed to mimic key energy-budget variables, permitting more precise tests of the energy-budget rule (Pietras & Hackenberg, 2001; Rode, Cosmides, Hell, & Tooby, 1999). To overcome the ethical issues of manipulating food intake, monetary outcomes have been substituted for food outcomes. Although optimal foraging models use energy gain (a correlate of reproductive fitness) as the currency that is maximized by foraging choices, the inclusion of other currencies, including monetary currencies, broadens the predictive scope of such models (see Hackenberg, 1998; Winterhalder & Smith, 2000).

For example, Pietras and Hackenberg (2001) gave subjects repeated choices between a fixed and variable number of points with the same mean value. Positive and negative "earning budgets" were generated by manipulating the number of points needed within a block of trials for those points to be exchanged for money at the session's end (i.e., the earnings requirement). During positive earnings-budget conditions, exclusive choices of the fixed option could meet the earnings requirement, but during negative earnings-budget conditions, only choices of the variable option (either exclusive choice of the variable option or alternating choices between the variable and fixed options) could produce a sufficient number of points. Consistent with the predictions of the energy-budget rule, choice was risk averse in positive earnings-budget conditions and risk prone in negative earnings-budget conditions.

These findings suggest that energy budgets may be modeled in the laboratory with an earnings budget in which monetary earnings and an earnings requirement are substituted for energy gains and an energy requirement. The predictions of energy-budget models can then be evaluated under these conditions by assuming that choice should minimize the probability of an earnings shortfall.

The present experiment extended this line of investigation to time-based choices in which subjects had a time-limited period in which to complete a fixed number of trials, simulating a time-limited foraging episode. Although risky choice for time-based outcomes has received less emphasis than risky choice for amounts, several energy-budget models predict that risky choice for time-based outcomes should also vary as a function of an organism's energy budget. Like the z-score model described above, time-based energy-budget models assume that a forager's choices should minimize the probability that net energy gains will fall below the energy requirement. For example, Stephens (1990) described a model to account for choice between two food options (delivering the same food amount) having a fixed and variable delay with the same mean value, t. If a forager needs to acquire the food within a fixed time period, T, to survive, then the energy-budget is positive when $T > t$ and negative when $T < t$. A forager can minimize the probability of shortfall under these conditions by choosing the fixed-delay option when the energy budget is positive and the variable-delay option when the energy budget is negative. Because the model predicts risk sensitivity over delays rather than amounts, Stephens called the model the "time-budget rule."

Zabludoff, Wecker, and Caraco (1988) proposed a similar model in which an organism's energy budget was described as

$$\begin{aligned} &T > Rt \quad \text{(positive energy budget)} \\ &T \leq Rt \quad \text{(negative energy budget)}, \end{aligned} \tag{1a}$$

where T is the total number of time units available to forage, t is the average delay to food (in time units per food unit), and R is the organism's energy requirement (in food units). Because choices for the fixed option minimize the probability of starvation when the energy budget is positive, and choices for the variable option minimize the probability of starvation when the energy budget is negative, this time-based energy budget, like Stephens (1990) model, predicts risk aversion under positive energy-budget conditions and risk proneness under negative energy-budget conditions. If t is sufficiently large or very small, however, such that

$$\begin{aligned} &t \geq (T/R) + x, \quad \text{or} \\ &t < (T/R) - x, \end{aligned} \tag{1b}$$

where x is the standard deviation of the delay distribution, then the probability of survival is impossible or certain, respectively, and neither risk aversion nor risk proneness is predicted.

Variants of the time-based energy-budget rule have been tested in several experiments with nonhuman animals as subjects, but the results generally do not show strong support for the model. Zabludoff et al. (1988), with rats, and Bateson and Kacelnik (1997), with starlings, found consistent preference for variable over fixed delays to food. Similarly, Case, Nichols, and Fantino (1995), with pigeons, found consistent preference for variable over fixed delays to water. Ha, Lehner, and Farley (1990) and Ha (1991), with jays, found either indifference or preference for variable- over fixed-ratio schedules of food delivery (schedules that typically generate, respectively, variable and relatively constant delays to food). Kirshenbaum, Szalda-Petree, and Haddad (2000), with rats, found that only when response effort was high did preference shift from risk proneness to risk aversion as predicted by the energy-budget rule.

Collectively, these results have found little or no sensitivity to time-based energy-budget manipulations. The lack of a consistent effect may be due to the difficulty of gaining precise control over the motivational operations that provide the basis for energy-budget manipulations. It may also relate to the many and varied ways in which energy-budget variables have been defined. In the studies reviewed above, energy budgets were manipulated by altering rate of food or water availability within a session (Bateson & Kacelnik, 1997; Case et al., 1995; Ha et al., 1990, Kirshenbaum et al., 2000), altering session duration (Case et al.; Ha et al.), altering food or water availability outside the session (Case et al.; Zabludoff et al., 1988), altering response effort (Kirshenbaum et al.), and altering ambient temperature (Ha, 1991).

By using an earnings budget in place of an energy budget, however, the variables that determine whether an earnings budget is positive or negative (i.e., the fixed and variable delays, and time period over which money can be earned) can be precisely controlled. The present experiment had two main objectives: (a) to investigate risk sensitivity in humans for fixed and variable delays across positive and negative earnings budgets (or alternatively, positive and negative time budgets, see Stephens, 1990), and (b) to evaluate the descriptive adequacy of energy-budget models designed to account for foraging-related choices under temporal constraints.

Subjects were given repeated choices between fixed and variable trial durations across repeated blocks of trials. Subjects had to complete a required number of trials within a fixed time period (hereafter called a delay threshold), T, for points exchangeable for money to be delivered at the end of the block. Positive and negative earnings budgets were arranged by manipulating the duration of this delay threshold. Under positive earnings-budget conditions, consistent choice of the fixed-delay option could complete the required number of trials within the delay threshold. Under negative earnings-budget conditions, only choice of the variable-delay option could meet the requirement (and then, only probabilistically).

These manipulations made it possible to evaluate choices in relation to the predictions of the time-based energy-budget model described by Zabludoff et al. (1988)—with positive earnings budgets defined as $T \geq Rt$ and negative earnings budgets defined as $T < Rt$—according to which risk aversion and risk proneness should occur under positive and negative energy-budget conditions, respectively. Although the present procedure differed from typical energy-budget procedures in that there were no gains during the choice period and no earnings requirement, the predictions of the time-based energy-budget model could be extended to choice in the present experiment by assuming that the requirement, R, equaled the number of trials that needed to be completed within the delay threshold (i.e., five trials) and t equaled the average delay per trial (i.e., 10 s).

In a previous risky-choice study with humans described above (Pietras & Hackenberg, 2001), choices under positive and negative earnings-budgets conditions occasionally deviated from the predictions of the energy-budget rule. That is, within a block, the variable option was sometimes selected under positive earnings-budgets conditions, and the fixed option was sometimes selected under negative earnings-budget conditions. A more local optimization model was developed to account for these deviations. The model predicted trial-by-trial (within block) choices that maximized earnings at specific combinations of trial position, accumulated earnings, and requirement level. Trial-by-trial choices were frequently consistent with the model's predictions. A similar model was developed and applied to within-block choices in the present study (see below) in an attempt to determine if deviations from the predictions of the time-based energy-budget rule could also be understood in relation to optimality criteria.

METHOD

Subjects

The subjects were 4 adult undergraduate students recruited through advertisements in a local university newspaper. Subjects were selected randomly from a pool of applicants based solely on schedule compatibility and naiveté with respect to behavioral issues and research.

Apparatus

Subjects were seated in an experimental chamber (2.21 m high by 1.21 m wide by 1.25 m deep) in front of a control panel containing several stimulus lights, counters, and response keys. An overhead light provided constant illumination throughout each session. A fan atop the chamber was also operated throughout each session to minimize extraneous noises. Three plastic response keys were used, each 2.5 cm in diameter and horizontally aligned at approximately eye level, with 8.2 cm between each. The keys could be backlit red, green, or yellow. A force of approximately 0.6 N was required to operate these keys and such responses were monitored by an attached computer programmed to record specific information about every response, as well as to control appropriate output stimuli within the chamber. Output stimuli included six 28-V white lights arranged in two vertically aligned sets of three spaced 8 cm apart, the bottommost located 8 cm above the side response keys, and two 3 cm by 6 cm six-digit electrical counters. These counters were vertically aligned 1.8 cm apart, with the top counter situated 20 cm below the right response key. Only minimal instructions were provided, and these were posted about 9 cm to the right of the control panel. The instructions read as follows: ‘‘You may earn points by pressing the response keys when lit. Press only one key at a time. Each point displayed on the upper, right counter is worth 2.5¢. Please remain seated. You will be informed when the session is over.''

Procedure

Before the beginning of the first session, the above instructions were read aloud to each subject. In subsequent sessions, subjects were told that ‘‘the instructions are the same as before.'' At the beginning of each session, both the bottom (delay) counter and the top (points) counter were set to 0. The session consisted of 12 blocks of five individual trials. To ensure adequate exposure to the consequences of selecting each option, the first six blocks consisted of five forced-choice trials, with only one of the two options available. The last six blocks each consisted of five free-choice trials in which both the fixed and variable options were available.

The initiation of each block was signaled by the onset of the six white lights. A trial-initiating response was required for each trial and was signaled by the onset of the red center keylight. During free-choice blocks, a single press on the center key turned off the center keylight and immediately illuminated the side keylights—one green, the other yellow, that flashed according to a 0.25 s on–off cycle. The key positions of the two colors were randomly determined for each trial. Five consecutive responses on either of the two side keys turned off the alternate (nonchosen) keylight and changed the keylight associated with the chosen key from flashing to constant illumination. This was done to delineate the choice periods from the delay periods of each trial. Selecting the yellow key produced a fixed delay period (10 s); selecting the green key produced a variable delay period (2 s or 18 s, $p = .5$). The cumulative delay counter incremented by one each second, but only ran during delay periods of each trial. The time required to complete the response requirement during the choice period was not included in the cumulative block time.

At the end of each block of trials, if the number on the cumulative delay counter did not exceed the delay threshold, then 10 points were added to the point counter. If the number on the delay counter exceeded the delay threshold, no points were added to the counter. The delay counter was then reset and the six white lights were extinguished. Trials were separated by a 7-s intertrial interval, during which all keys were dark and the delay counter was inoperative. To keep the block initiation and session duration constant and independent of choices (i.e., to prevent the short block and session durations that could occasionally result from choices of the variable option), each block of trials was followed by an interblock interval of 100 s minus the total of the delays during that block.

Forced-choice blocks were identical to free-choice blocks (points exchangeable for money were also delivered during forced-choice blocks) except that only one of the two side keys was lit, with its position randomly determined for each trial. The option presented during each forced-choice block (fixed or variable) was randomly determined at the start of each block of trials and remained consistent throughout that block, with the restriction that three of the six blocks of five trials involved the variable option (green key light) and the other three blocks involved the fixed option (yellow keylight).

The delay threshold was manipulated across conditions. During positive earnings-budget conditions, the delay threshold was set at 50 s, such that exclusive preference for the fixed option would always result in point earnings, but exclusive preference for the variable option would do so only half of the time. During negative earnings-budget conditions, the delay threshold was set at 40 s or 32 s, such that exclusive preference for the fixed option would never result in point earnings but exclusive preference for the variable option would earn points with $p = .19$. (The probability of earnings points for exclusive choices of the variable option was identical when the delay threshold was 40 s and 32 s because in both conditions the delay threshold could only be met if choices produced the short [2-s] delay period in four of the five trials. The primary difference between the two delay-threshold conditions was that when the delay threshold was 40 s it was possible to earn points during a block by switching from the variable option to the fixed option after choices of the variable option produced two short [2-s] delay periods, whereas when the delay threshold was 32 s, it was possible to earn points by switching from the variable option to the fixed only after choices of the variable option produced three short [2-s] delay periods.)

All subjects were initially exposed to the 50-s threshold positive-budget condition, then the 40 s-threshold negative budget condition, followed by another 50-s threshold positive-budget condition and finally the 32 s-threshold negative budget condition. Table 1 shows the sequence and number of sessions per condition for each subject. Experimental conditions remained in effect for a minimum of five sessions and until the number of fixed (free) choices (out of 30) during three consecutive sessions was stable by visual inspection. Choices were considered stable when

Table 1

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

Earnings-budget condition	Subject															
	10				11				12				13			
Positive (T = 50 s)	1	(7)	3	(6)	1	(9)	3	(5)	1	(5)	3	(5)	1	(6)	3	(5)
Negative (T = 40 s)	2	(5)			2	(5)			2	(5)			2	(5)		
Negative (T = 32 s)	4	(5)			4	(5)			4	(5)			4	(5)		

there was little session-to-session variability and no trends in the direction predicted in the following condition. Each subject participated in two sessions per day Monday through Friday at approximately the same time of day, with a brief (approximately 1 min) break between sessions.

Following each session, subjects were presented with a receipt for an amount equal to their session earnings (2.5¢ per point) plus $1.50. At the end of the subject's participation, a check for the sum of these amounts was mailed to the subject. Overall earnings averaged $6.20 per hour.

Subjects 10 and 11 were exposed to additional trial-correlated stimuli during their initial sessions of the experiment (13 and 4 sessions for Subjects 10 and 11, respectively). Due to an intermittent apparatus failure, however, these additional stimuli were eliminated and not subsequently used. There was no indication that this change had any effect on performance.

RESULTS

Figure 1 shows, for each subject, the number of choices for the fixed option (closed circles) during the 30 choice trials per session across conditions. Exclusive or nearly exclusive preference for the fixed option was established under both positive-budget conditions (T = 50 s) for all 4 subjects. When the criterion was changed to T = 40 s, preference

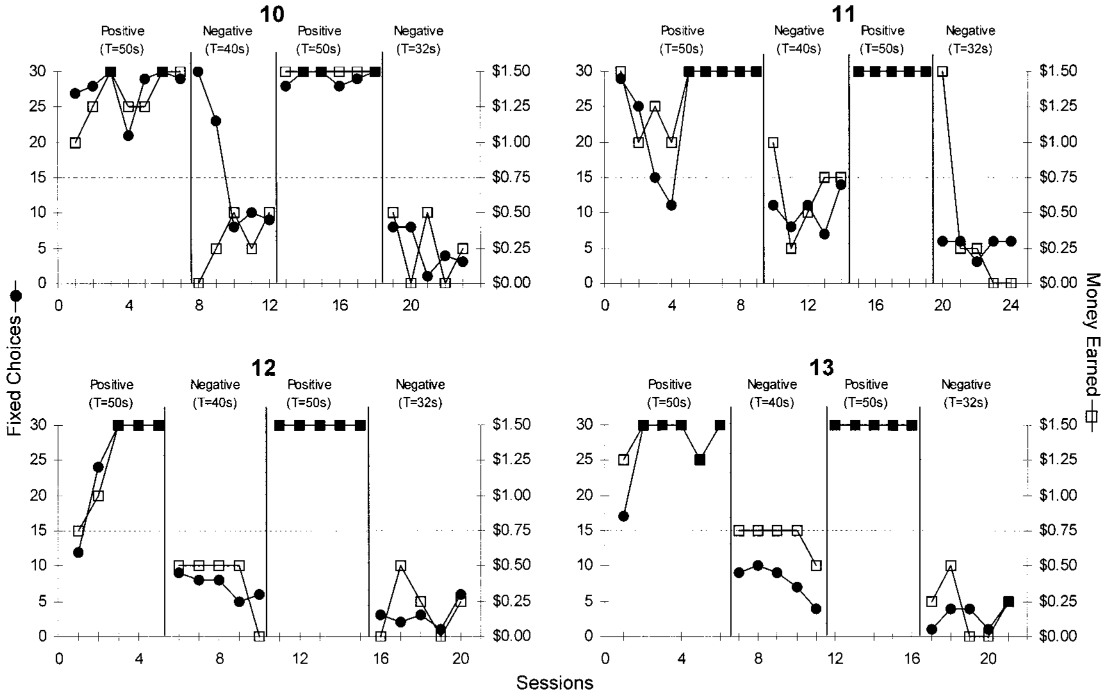

Fig. 1. Number of choices for the fixed option (closed circles, left y-axis) and the amount of money earned (open boxes, right y-axis) in the 30 choice trials per session for each subject.

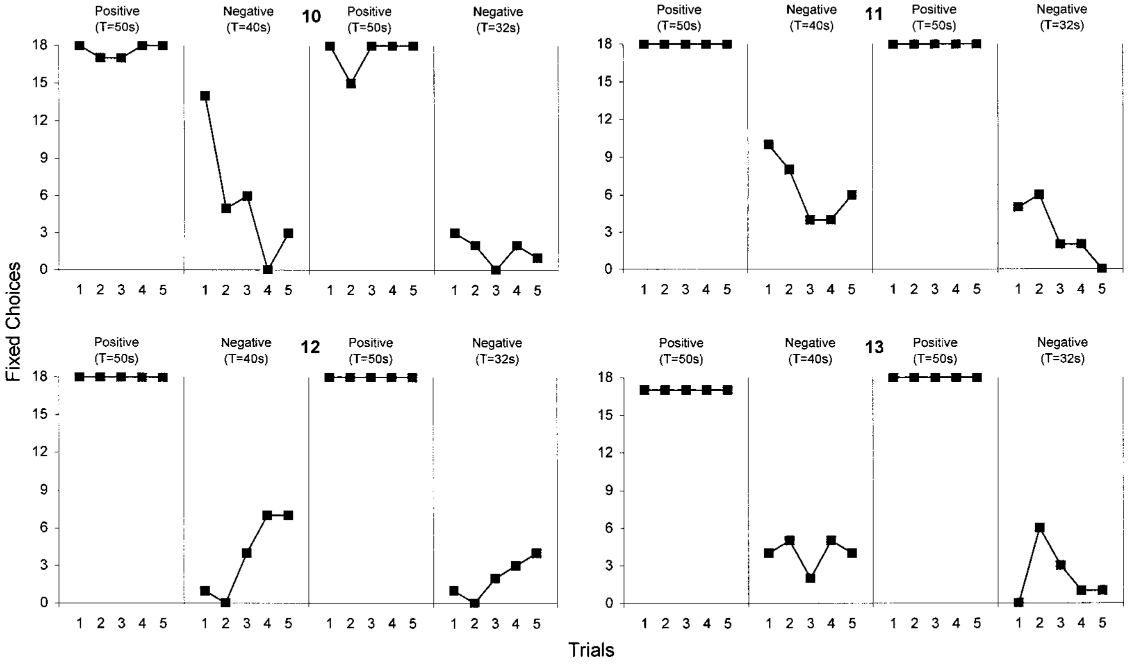

Fig. 2. Number of choices for the fixed option as a function of trial position for each subject across the final three sessions of each condition.

shifted toward the variable option with between 64% (Subject 11) and 79% (Subject 12) of choices for the variable option during the final three sessions of the condition. An even more extreme shift in preference occurred with the final negative-budget condition (T = 32 s), with 83% (Subject 11) to 91% (Subject 10) of choices for the variable option. With one exception (the second condition for Subject 10), the shifts in preference were rapid, occurring within the first session of the new condition. Such rapid adjustment to the changed contingencies was presumably due to the 30 forced-choice trials subjects experienced in the first half of each session.

The overall pattern of choices was in good agreement with the predictions of the time-based energy-budget rule proposed by Zabludoff et al. (1988). Across subjects, 89% of choices from the stable sessions were in perfect accord with the model. That is, in 89% of choice trials from the final three sessions of a condition, the fixed option was chosen under positive earnings-budget conditions and the variable option was chosen under negative earnings-budget conditions.

The total amount of money earned during the free choice trials of each session is also shown in Figure 1 (open boxes). More money was earned during the positive-budget conditions (averaging at least $1.25 per session) than during either of the negative-budget conditions (ranging from an average of $0.20 to $0.40 per session during the R = 32 s condition to an average of $0.30 to $0.70 per session during the R = 40 s condition).

Figure 2 shows the number of choices for the fixed option across the five trials within a block of choices. Data are from the final three sessions of each condition (18 blocks total). Consistent with Figure 1, all subjects showed an exclusive or near-exclusive preference for the fixed option during the positive-budget conditions. In the negative-budget conditions, Subjects 10, 11, and 13 all showed a decreasing trend or no trend in choices for the fixed option across trials. Only Subject 12 chose the fixed option more frequently in later trials (from 3% fixed in Trials 1 and 2 to 39% in Trials 4 and 5 when T = 40 s, and from 3% to 19% when T = 32 s). A more detailed characterization of Subject 12's performance is presented below.

The energy-budget rule is a static optimization model that predicts exclusive preference for the fixed or variable option. In the

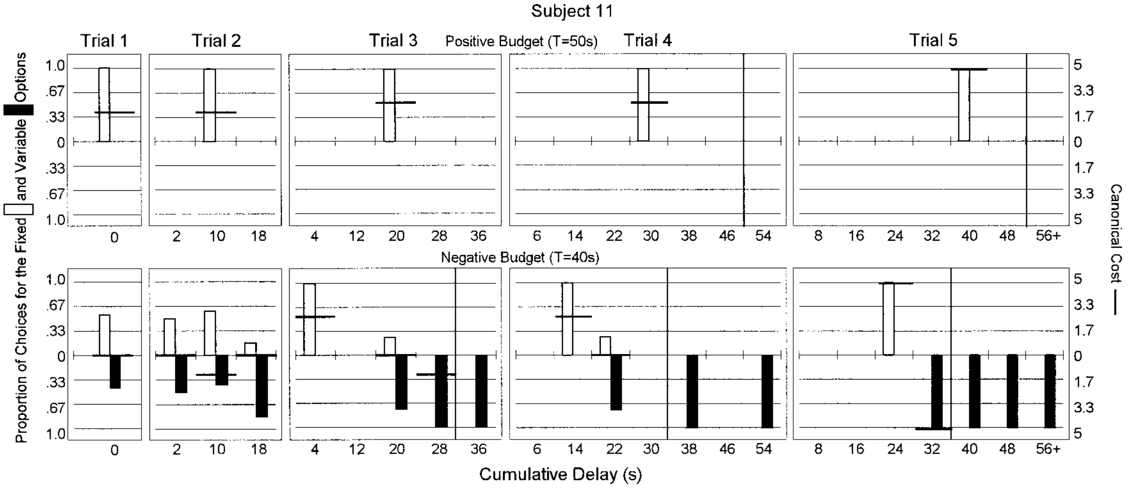

Fig. 3. Proportion of choices for the fixed (open bars) and variable (filled bars) options at each trial position as a function of the cumulative delay value during the final three sessions of the initial positive ($T = 50$ s) and negative ($T = 40$ s) earnings-budget conditions for Subject 11. The short, horizontal lines at some cumulative delay values indicate the canonical costs (the average loss in earnings from nonoptimal choices). Cost lines above the *x*-axis indicate that choices for the fixed option were optimal whereas lines below the *x*-axis indicate that choices for the variable option were optimal. Cost lines on the *x*-axis (at zero) indicate that neither choice for the fixed or variable option was designated as optimal. Bars to the right of the vertical line show choices that occurred when both fixed and variable choices would exceed the delay threshold.

present procedures, however, switching between the fixed and variable option within a block of trials could occasionally increase the probability of meeting the requirements. Optimal choices therefore depended on the relation between fixed and variable delays, the delay threshold (i.e., requirement), the specific trial, and the cumulative trial time within a block. When choice varies as a function of current state (e.g., cumulative delay), and the current state is determined by previous choices, *dynamic* optimization models may be used to predict optimal behavior (Mangel & Clark, 1988; Stephens & Krebs, 1986). Dynamic optimization models predict optimal choices across successive time periods at each possible state value. They also predict the canonical costs, or estimated loss in earnings from nonoptimal choices (Houston & McNamara, 1988). In contrast to the energy-budget rule, dynamic optimization models predict that in the present procedure, preference may switch between the fixed and variable option across trials within a block depending on the cumulative delay, trial number, and delay threshold.

Although choices in the present study were generally in accord with the predictions of the time-based energy-budget rule, choices sometimes deviated from the model's predictions. Within-block choices were therefore analyzed in relation to the predictions of a dynamic optimization model and also to canonical-cost measures. The objective of this analysis was to determine if any of the deviations from the time-based energy-budget rule could be understood in relation to optimization principles. A description of the model and its predictions is presented in the Appendix.

Within-block choices were in good accord with the model's predictions. Across subjects, 95% of the choices made in the final three sessions were consistent with the model. The within-session data for Subjects 11 and 12, the 2 subjects whose choices were most consistent with the model's predictions, are displayed in greater detail in Figures 3 and 4. These figures present data from each of the five trials for the last three sessions of the first positive and negative earnings-budget conditions (18 blocks total). All of the possible cumulative delay values at the beginning of each trial are represented on the *x*-axis for the trial in which they could have occurred (e.g., 0 s at Trial 1, 2 s, 10 s, and 18 s at Trial 2, etc., see Appendix). The bar graphs represent the proportion of fixed (white bars above the *x*-

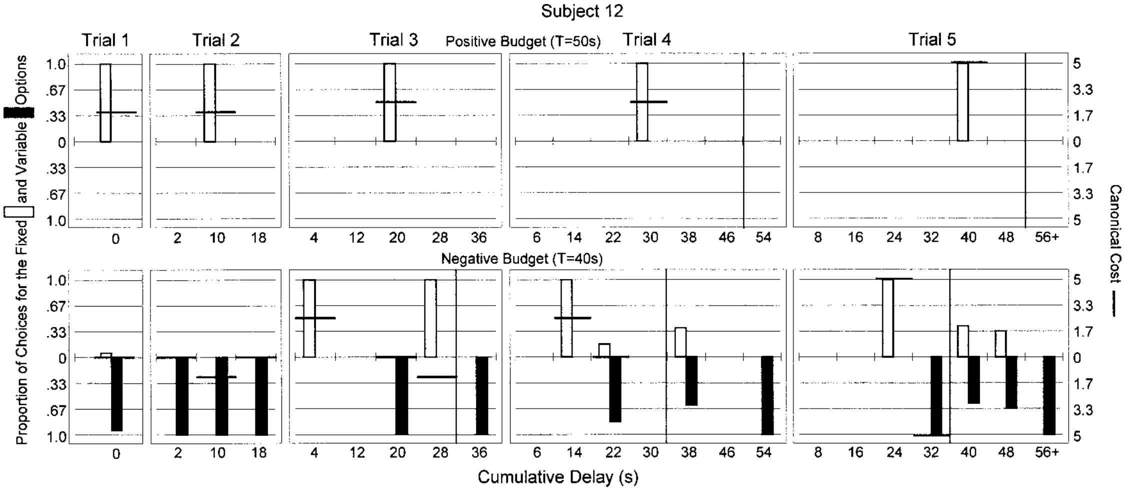

Fig. 4. Proportion of choices for the fixed (open bars) and variable (filled bars) options at each trial position as a function of the cumulative delay value during the final three sessions of the initial positive (T = 50 s) and negative (T = 40 s) earnings budget conditions for Subject 12. All other details are the same as in Figure 3.

axis) and variable (black bars below the *x*-axis) choices at each delay value. Most of the bars on this figure extend to the ceiling (for fixed choices) or floor (for variable choices), indicating an exclusive preference for the fixed- or variable-delay option.

The horizontal lines at each cumulative delay value show the canonical costs, or the average number of points lost by selecting the nonoptimal alternative. These canonical costs are also listed in the Appendix in Tables A1 to A3, along with the canonical costs at all other combinations of delay threshold, trial number, and cumulative-delay value for which an optimal choice was predicted. For clarity, cost lines are plotted above the *x*-axis when choice of the fixed-delay option is optimal and below the *x*-axis when choice of the variable-delay option is optimal. The exact distance of the line from the *x*-axis (i.e., the magnitude of the canonical cost) indicates the degree to which a choice was optimal. Because choices occurring at cumulative delay values to the right of the vertical lines exceeded the delay threshold (T) and could not produce points, neither choice was designated as optimal.

In the T = 50 positive earnings-budget condition, both Subjects 11 (Figure 3) and 12 (Figure 4) selected the fixed option exclusively when it was optimal to do so. In the T = 40-s negative earnings-budget condition, Subject 11 always chose the fixed option when fixed choices were optimal, and except for a single choice of the fixed option at Trial 2 (with a 10-s cumulative delay), always chose the variable option when variable choices were optimal. Subject 12 selected the variable option whenever such choices were optimal (at 10 s in Trial 2 and at 32 s in Trial 5), except for a single choice for the fixed option (at 28 s in Trial 3). More notably, this subject selected the fixed option whenever it was optimal to do so (at 4 s in Trial 3, 14 s in Trial 4, and 24 s in Trial 5), with no exceptions. For both subjects, deviations from optimal during the T = 40-s negative earnings-budget condition occurred when costs were low (costs = 1.25); no deviations occurred when costs were higher (costs = 2.5 or 5).

DISCUSSION

Risky choice for delayed outcomes was investigated in adult humans across earnings-budget manipulations designed to model positive and negative energy budgets. Consistent with the predictions of an energy-budget model designed to account for foraging choices under temporal constraints (Zabludoff et al., 1988), choice was risk averse during positive earnings-budget conditions and risk prone during negative earnings-budget conditions.

The time-based energy-budget rule provided a reasonably good description of the results, but it did not account for all of the choices. In particular, there was a higher frequency of fixed choices under negative-budget conditions than predicted by the model. We therefore employed a second type of optimization model—a dynamic model that took into account an additional potentially relevant variable: cumulative delay time (i.e., the number shown on the cumulative delay counter) at the time of each choice. Unlike the energy-budget rule, which predicts that choices remain consistent within a foraging episode, the dynamic model predicts occasional within-block changes in preference. Models of this sort thus embody the suggestion by Houston and McNamara (1982) and others that switching between risky and nonrisky options within a foraging episode can sometimes enhance fitness. At some combination of energy stores, rate of prey capture, and energy requirements, it is optimal to switch from risky to nonrisky choice, and vice versa. So, too, in the present procedures, at some combinations of earnings, cumulative-delay time, and trial position, it is optimal to switch from variable to fixed or from fixed to variable.

During negative earnings-budget conditions, for example, following a sequence of variable choices in which short delays were experienced (i.e., 2 s), the model predicts that preference should switch from the variable to the fixed-delay option. Switching under these conditions maximizes potential earnings by increasing the probability of meeting the delay threshold: Persisting with the variable-delay option during the negative earnings-budget (T = 40 s) condition would meet the delay threshold with p = .19, whereas switching from the variable to the fixed delay option after experiencing a sequence of short delays would increase the probability to .38. For Subjects 11 and 12, the dynamic model predicted 21 of 22 instances in which it was optimal to select the fixed option under T = 40 s and T = 32 s negative-budget conditions. Although the model added little to the description of the other two data sets, the positive evidence should be sufficient to illustrate the utility of a dynamic optimization model with a simple decision rule: Select whichever option has the momentarily higher probability of meeting the delay threshold.

The risk sensitivity demonstrated here is in accord with the results of recent earnings-budget studies with human subjects (e.g., Pietras & Hackenberg, 2001; Rode et al., 1999), but contrasts with most previous risky-choice research with humans. Prior studies have shown across a range of conditions that choice is consistently risk averse, whether the outcomes are fixed and variable reinforcer amounts or fixed and variable reinforcer delays (e.g., Kohn, Kohn, & Staddon, 1992), or whether the outcomes are hypothetical and presented verbally (e.g., Rachlin, Raineri, & Cross, 1991; Schneider & Lopes, 1986), or real and directly experienced (e.g., Lane & Cherek, 2000; Schmitt & Whitmeyer, 1990). Only when choice outcomes are losses (i.e., negative monetary amounts) has greater risk proneness been observed (e.g., Hershey & Schoemaker, 1980; Kahneman & Tversky, 1979; Tversky & Kahneman, 1992). The present results therefore show that earnings-budget variables can produce reliable risk sensitivity in individual subjects in a context defined by reinforcer gain. More generally, these and other recent results show that, similar to an energy requirement, contingencies that restrict which choices produce payoffs such as an earnings requirement (Pietras & Hackenberg) or need level (i.e., a gain criterion, Rode et al.) can influence risk sensitivity.

The present results differ, however, from analogous studies with nonhuman subjects in which consistent preference for variable over fixed delays is generally seen across energy-budget manipulations (Bateson & Kacelnik, 1997; Case et al., 1995; Ha, 1991; Ha et al., 1990; Zabludoff et al., 1988). Such differences may reflect differences in procedure. One potentially important difference concerns the nature of the reinforcement system. In experiments with nonhumans, choices produce unconditioned reinforcers such as food or water that are typically consumed as they are earned. Conversely, in experiments with humans, choices typically produce token reinforcers (points) that are only later exchangeable for other reinforcers. Because the value of such token reinforcers depends on their relation to more remote sources of reinforcement, token reinforcers lack the immediate hedonic value of consumable reinforcers. As a result, the two reinforcement systems may give rise to different choice patterns with consumable reinforcers showing greater time urgency than token reinforcers. The differential sensitivity to remote outcomes seen in the present study may therefore be a product of a token reinforcement system. Future research should address this possibility, both by examining human choice with consumable-type reinforcers (e.g., Forzano & Logue, 1994; Hackenberg & Pietras, 2000; Logue & King, 1991; Navarick, 1996) and nonhuman choice with token-type reinforcers (e.g., Jackson & Hackenberg, 1996).

Because token reinforcers were used instead of consumable reinforcers, it is possible that the actual delays on the fixed and variable options were unimportant and that variables other than delays influenced choice. In the present procedure, unlike previous energy-budget studies with nonhumans, time-correlated stimuli (i.e., the addition of one point per second to the cumulative delay counter) were programmed during the delay periods. Possibly, these stimuli (points) and not the delays affected preference. More specifically, maintaining the number of points on the cumulative delay counter below the requirement, rather than maintaining the cumulative delay below the delay threshold, may have been the critical determinant of choice. Additional research could investigate the role of the time-correlated stimuli in this procedure by examining choice under conditions in which the cumulative delay counter did not increment during delay periods. Regardless of whether delays or point amounts controlled choice, however, the orderly shifts in preference across conditions indicate that choice was sensitive to the earnings budget.

Another procedural difference separating human from nonhuman energy-budget studies concerns the manner in which budget variables are manipulated. An energy budget is a joint function of current energy reserves, availability of resources, and minimum subsistence requirements. In studies with nonhumans, energy budgets are typically manipulated by way of alterations in current energy reserves (e.g., through deprivation procedures) and resource availability (e.g., through changes in reinforcement frequency). Few studies have examined the effects of subsistence requirements as an independent variable in its own right (see Caraco et al., 1990, for an interesting exception). The relative dearth of studies along these lines may be due to the difficulties inherent in precise measurement of, and control over, the minimum energy requirements needed for survival. With monetary currencies substituted for nutritional currencies, however, the problem becomes more analytically tractable. The minimum subsistence requirements can be clearly and operationally defined in relation to energy reserves (accumulated points) and rate of gain (delay to and amount of points), simulating key features of an energy budget but without the life–death consequences faced by a foraging animal. The use of monetary currencies therefore sacrifices ecological realism for experimental rigor and analytic tractability.

The present procedures and results join with several others in demonstrating the utility of laboratory methods for analyzing human behavior in relation to optimality criteria (see Hackenberg, 1998, for a review). Stockhorst (1994) found that humans' choices in a successive-choice procedure designed to model search and handling components of a foraging episode were generally in good agreement with the optimal diet model (Charnov, 1976a; MacArthur & Pianka, 1966). Hackenberg and colleagues (Hackenberg & Axtell, 1993; Jacobs & Hackenberg, 1996) found that humans' choices in a laboratory task designed to model foraging in a patchy environment were consistent with the predictions of the marginal value theorem (Charnov, 1976b). Kraft and Baum (2001), Sokolowski, Tonneau, and Freixa i Baqué (1999), and Madden, Peden and Yamaguchi (2002) showed that humans' choices in a laboratory analogue of group foraging were generally consistent with the predictions of the ideal-free distribution model (Fretwell & Lucas, 1970).

Laboratory methods also promise to provide important insights into the proximate behavioral mechanisms responsible for the aggregate outcomes to which optimization models are typically applied. Although classical optimization models have traditionally been silent with respect to such mechanisms, recent models have placed greater emphasis on the elucidation of local decision rules, or "rules of thumb," underlying the more global outcomes (e.g., Bateson & Kacelnik, 1998; Fantino & Abarca, 1985; Hackenberg & Hineline, 1992; Shettleworth, 1998; Stephens & Anderson, 2001).

Models of this sort combine questions about survival value (the ecological circumstances surrounding a particular behavior pattern) with questions about current function (the behavioral mechanisms responsible for it). The local decision rule revealed by the present analysis—choose the option with the highest payoff probability—could have important selective advantages in the natural environments in which behavior evolved, including human ancestral environments. To be sure, the earnings budgets arranged in the present study and the energy budgets arranged by life–death choices in ancestral environments differ in important ways. It may not be unreasonable to suppose, however, that the kind of sensitivity to monetary consequences demonstrated here is part of a more general sensitivity to probabilistic events in the environment. As such, a better understanding of the variables governing current choices may shed light on the proximate behavioral mechanisms through which adaptive behavior has evolved.

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APPENDIX

A dynamic optimization model was constructed to predict choices across successive trials within a block as a function of cumulative delay (trial) time and position within the block (see Houston and McNamara, 1988; Mangel and Clark, 1988, for a description of dynamic modeling). The function relating the cumulative delay time t_c to points at the end of the block (an analogue of a terminal fitness function) was:

$$F(t_c, N, N) = \begin{cases} 0 \text{ points} & \text{if } t_c > T \\ 10 \text{ points} & \text{if } t_c \leq T \end{cases} \quad \text{(A1)}$$

where T is the delay threshold and N is the total number of trials. The dynamic programming equation was:

$$\begin{aligned} &F(t_c, n, N) \\ &\quad = \text{Max } \{[F(t_c', n + 1, N)] \\ &\qquad\qquad \text{(fixed-delay option)}\} \\ &\qquad \{(p)[F(t_c', n + 1, N)] + (1 - p) \\ &\qquad\quad [F(t_c'', n + 1, N)] \\ &\qquad\quad \text{(variable-delay option)}\} \qquad \text{(A2)} \end{aligned}$$

where $F(t_c, n, N)$ is the mean (expected) earnings, n is the trial number (numbered forward), and p is the probability of each delay interval ($p = 1$ for the fixed option and $p = .5$ for the variable option). The state dynamics were:

$$\begin{aligned} \text{Fixed option:} \quad & t_c' = t_c + 10 \text{ s} \\ \text{Variable option:} \quad & t_c' = t_c + 2 \text{ s} \quad \text{or} \\ & t_c'' = t_c + 18 \text{ s.} \qquad \text{(A3)} \end{aligned}$$

Tables A1 to A3 present the predictions of the model at each delay threshold. Also shown are the canonical costs, or losses in earnings from selecting the nonoptimal choice, calculated by subtracting the expected earnings of nonoptimal choices from the expected earnings of optimal choices. For a more detailed description of how within-block predictions were calculated see Pietras and Hackenberg (2001).

Table A1

Expected point earnings for selections of the fixed (F) and variable (V) delay option for each cumulative delay time, t_c, during the Positive Earnings-Budget ($T = 50$ s) condition. The optimal choice is in italics. Cost values are the canonical costs or loss in point earnings from selecting the nonoptimal choice. F(t_c, n, N) shows that the number of points delivered for the cumulative delay time following the fifth (final) trial of a block.

Cumulative delay time (t_c) in seconds	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			F
	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	(t_c, n, N)
0	*10*	8.125	1.875													
2				10	10											
4							10	10								
6										10	10					
8													10	10		
10				*10*	8.125	1.875										10
12							10	10								10
14										10	10					10
16													10	10		10
18				6.25	6.25											10
20							*10*	7.5	2.5							10
22										10	10					10
24													10	10		10
26																10
28							5	*6.25*	1.25							10
30										*10*	7.5	2.5				10
32													10	10		10
34																10
36							2.5	2.5								10
38										5	5					10
40													*10*	5	5	10
42																10
46										0	*2.5*	2.5				10
48													0	*5*	5	10
50																10
54										0	0					0
56													0	0		0
58																0
64													0	0		0
66																0
72													0	0		0
74																0
82																0
90																0

Table A2

Expected point earnings for selections of the fixed (F) and variable (V) delay option for each cumulative delay time, t_c, during the Negative Earnings-Budget (T = 40 s) condition. All other details are the same as in Table A1.

Cumulative delay time (t_c) in seconds	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F (t_c, n, N)
0	3.75	3.75														
2				6.25	6.25											
4							*10*	7.5	2.5							
6										10	10					
8													10	10		
10				2.5	*3.75*	1.25										10
12							5	*6.25*	1.25							10
14										*10*	7.5	2.5				10
16													10	10		10
18				1.25	1.25											10
20							2.5	2.5								10
22										5	5					10
24													*10*	5	5	10
26																10
28																10
30																10
32																10
34																10
36																10
38													0	*5*		10
40																10
42																0
46																0
48										0	*2.5*		0	0		0
50																0
54																0
56													0	0		0
58										0	0					0
64																0
66							0	*1.25*					0	0		0
72										0	0					0
74													0	0		0
82																0
90							0	0	1.25	0	0	2.5	0	0	5	0

Table A3

Expected point earnings for selections of the fixed (F) and variable (V) delay option for each cumulative delay, t_c, during the Negative Earnings-Budget ($T = 32$ s) condition. All other details are the same as in Table A1.

Cumulative delay time (t_c) in seconds	Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F	V	Cost	F (t_c, n, N)
0	1.25	*2.1875*	0.9375													
2				2.5	*3.75*	1.25										
4							5	*6.25*	1.25							
6										*10*	7.5	2.5				
8													10	10		
10				1.25	1.25											10
12							2.5	2.5								10
14										5	5					10
16													*10*	5	5	10
18				0	*0.625*	0.625										10
20							0	*1.25*	1.25							10
22										0	*2.5*	2.5				10
24													0	*5*	5	10
26																10
28							0	0								10
30										0	0					10
32													0	0		10
34																0
36							0	0								0
38										0	0					0
40													0	0		0
42																0
46										0	0					0
48													0	0		0
50																0
54										0	0					0
56													0	0		0
58																0
64													0	0		0
66																0
72													0	0		0
74																0
82																0
90																0