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ScienceDirect
Behavioural Processes 75 (2007) 231–236
Behavioural Processes
www.elsevier.com/locate/behavproc

Short communication

A comparison of two algorithms in computerized temporal discounting procedures

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Received 9 September 2006; received in revised form 7 November 2006; accepted 19 November 2006

Abstract

Two algorithms are commonly applied in computerized temporal discounting procedures (Decreasing Adjustment and Double-Limit Algorithms); however, the degree to which the two algorithms produce similar patterns of discounting is unknown. The present experiment compared the two common algorithms across sign (gains and losses) and magnitude ($10 and $1000) conditions. Twenty participants made choices between larger later and smaller sooner alternatives that were presented by each of the algorithms in separate conditions. Strong correlations were found between the two measures; however, the Decreasing Adjustment Algorithm tended to produce lower indifference points and higher rates of discounting than the Double-Limit Algorithm. Both algorithms found significant magnitude effects. Less consistent results were found when comparing the two algorithms across sign. The present results suggest that researchers should apply caution when making comparisons between outcomes of delay discounting studies that have used the two different algorithms. However, the interpretation of findings from individual studies is probably not strongly affected by the use of different computer algorithms.

Keywords: Decreasing Adjustment; Delay discounting; Double-Limit; Indifference points; Methodological; Temporal discounting

1. Introduction

Temporal discounting has gained considerable attention across a broad range of research fields, including behavioral pharmacology (e.g., Perry et al., 2005), addiction (e.g., Bickel and Marsch, 2001; Bickel et al., 2006), economics (e.g., Loewenstein and Elster, 1992), evolutionary psychology (e.g., Daly and Wilson, 2005), and self-control (e.g., Rachlin, 2000). Researchers from each of these fields have constructed their own procedures that can be used to estimate the rate at which the delay until a reward is received decreases its subjective value. For example, $100 in 1 day is worth more to most of us than $100 in 1 year. The complete range of available discounting procedures varies widely in terms of methodology. For instance, discounting functions among rats and pigeons (e.g., Mazur, 1987) are usually determined using an experiential reinforcer (i.e., a reinforcer which is delivered repeatedly during the session, allowing the experience of a delay to affect subsequent choices), delays of seconds, stability criteria, and an effortful task (e.g., lever pushing); whereas human discounting experiments (e.g., Richards et al., 1999) typically use hypothetical (non-experiential) rewards, include delays up to several years, lack stability criteria, and involve mouse-clicks or other minimal effort responses.

The variety of currently available discounting procedures has caused some researchers to question whether all procedures are actually measuring the same behavioral process (see Madden et al., 2004; Navarick, 2004). Nonetheless, comparisons between results of discounting studies collected from different laboratories and experimental procedures are not uncommon (for examples see below). Admittedly, the ideal suggestion would be for standardized procedures to be used whenever possible (Baron and Derenne, 2000). At the very least, when making comparisons between different procedures used to measure discounting, researchers retain a responsibility of ensuring that they are aware of the degree to which these proce-

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doi:10.1016/j.beproc.2007.02.005

dures are measuring the same behavioral process. Rather than discouraging comparisons, it may be more beneficial to compare experimentally different procedures and methodological variations that have been commonly used to study discounting.

Several methodological variations have been compared experimentally by having the same participants complete two or more different discounting procedures. Johnson and Bickel (2002) and Madden et al. (2003, 2004) tested participants' discounting of real and hypothetical delayed rewards and found the two rewards were similarly discounted. Reynolds (2006) compared results from an experiential discounting task (where real rewards were earned on 35% of the trials) and a hypothetical discounting task and found strong correlations between the two measures. Several other empirical studies have previously evaluated different methods of deriving discounting functions (e.g., paper assessments versus computerized, Epstein et al., 2003; single option versus multiple option choice trials, Hinson et al., 2003; steady state versus one-time shot, Lagorio and Madden, 2005). These studies have revealed that careful examination of methodological variations can serve as a useful guide about the generality and limitations of temporal discounting. A useful continuation of these previous examinations would be to compare the common algorithms that are applied in computerized discounting procedures.

Among human participants, computerized temporal discounting procedures ask participants to choose between an immediate outcome and a delayed outcome on each of numerous trials. The value of the immediate outcome is adjusted from trial to trial according to a specified algorithm with the goal of approaching the point at which both outcomes are subjectively equivalent. One commonly used algorithm is based on a Decreasing Adjustment (Du et al., 2002). The first choice is always between the delayed amount and exactly half of the delayed amount. Following each choice the value of the adjusting outcome is increased or decreased by half of the previous adjustment, depending on the choice of the participant. The procedure continues until a specified number of trials has elapsed, at which time the value that would have been presented as the adjusting outcome on the next trial is accepted as the indifference point.

A second commonly used algorithm is the Double-Limit procedure (Richards et al., 1999). The first choice is between the delayed amount and a probabilistically selected adjusting amount that is between 0% and 100% of the value of the delayed amount. Following each choice, an adjusting outcome is probabilistically selected from a range of values that is narrowed when consistent choices are made by the participant. This algorithm continues until the participant responds consistently within a narrow range of values that correspond to a single indifference point. The indifference point is calculated by taking the value of the adjusting outcome amount after the algorithm has converged. The purpose of this study was to determine whether these two commonly used computerized discounting procedures produce similar discounting functions when the same participants are exposed to both procedures.

2. Materials and methods

2.1. Participants

Twenty participants (12 male, 8 female) between 21 and 56 years of age, with a median age of 43, were recruited through regional newspaper advertisements. There were no exclusion criteria beyond the ability to complete the one-session study; therefore there was no predetermination of eligible participants, and demographics were collected during the session. The ethnic distribution in the study was 55% Caucasian and 45% African American. Participants volunteered and gave written informed consent for the study, which was approved by the University of Arkansas for Medical Sciences Institutional Review Board. All 20 participants that were recruited finished the study and were compensated \$15 h^{-1} for the time that they spent in the lab.

2.2. Procedure

2.2.1. General procedure

The order in which the two temporal discounting procedures were presented was counterbalanced across participants. In both discounting procedures, immediate (adjusting) and delayed (standard) outcomes were presented on the monitor. Mouse clicks were then used to indicate the preferred outcome in each trial. On the computer monitor, the adjusting outcome was always presented in the left of two command boxes while the standard outcome was always presented in the right box. The text on the adjusting outcome command box said "\$(*money amount*) right now", with the amount determined by the programmed algorithm. The text of the standard outcome command box said "\$(*money amount*) in (*delay*)", with the money amount and delay determined by the Magnitude and Delay conditions, respectively.

Indifference points were determined at seven delays (1 day, 1 week, 1 month, 6 months, 1 year, 5 years, and 25 years) for two magnitudes (\$10 and \$1000) of hypothetical gains and losses. Algorithm, Magnitude, and Sign conditions were counterbalanced across participants. Delays were always presented in increasing length. Participants were randomly assigned an order of presentation of conditions with the restriction that an equal number of participants completed each order. For each of the algorithms, a total of 28 indifference points (one for each combination of standard magnitude, delay, and gain/loss) were collected from each participant.

2.2.2. Double-Limit Algorithm (Richards etal., 1999)

A precise description of the algorithm used in this study was provided by Johnson and Bickel (2002). The following description summarizes the aspects of the algorithm of direct interest in this report. In each choice trial, participants chose between two hypothetical monetary outcomes: an immediate outcome and an outcome at some temporal distance in the future. In each condition, the immediate outcome (called the adjusting outcome) adjusted (increased or decreased) from trial to trial while the future outcome (called the standard outcome) remained constant. On the first trial, the algorithm selected an adjusting outcome, which was a multiple of 2% of the standard outcome, from values ranging from 0% to 100% of the standard outcome. For each choice thereafter, the adjusting outcome was selected probabilistically from a range of values that narrowed when the participant made consistent choices. If participants did not choose consistently, then the range of values did not narrow. This prevented occasional mistaken responses from affecting the determination of indifference points. The algorithm continued until the participant responded consistently across a range of values for the adjusting outcome that had converged to a multiple of 2% of the standard outcome. The value of the adjusting outcome was then selected as the indifference point. The algorithm usually required 5–15 trials to reach a single indifference point (i.e., an indifference point for a single delay and a single monetary magnitude).

2.2.3. *Decreasing Adjustment Algorithm (Du et al., 2002)*

This procedure was identical in all respects to the Double-Limit Algorithm with the exception of the algorithm used to determine indifference points. On the first trial, the adjusting alternative was equal to half of the standard alternative. For instance, if the standard alternative was \$10.00, then the adjusting alternative would have been \$5.00. For each choice thereafter, choice of the standard alternative resulted in increasing the adjusting alternative by half of the previous adjustment. Choice of the adjusting alternative resulted in decreasing the adjusting amount by half of the previous adjustment. After each choice response a command box appeared on the screen that could be removed by pressing the space bar to accept, or the backspace key to reject, the choice that had just been made. If participants rejected their choice, then the algorithm returned to the trial until the participant responded again. The next trial was presented only after the acceptance of a choice response. This prevented occasional mistaken responses from affecting the determination of indifference points. This algorithm continued for six trials, when an indifference point was determined. Indifference points were calculated by determining the value that would have been presented in the next trial (trial 7) as the adjusting outcome; with the exception that the final indifference point was rounded to three significant digits.

2.2.4. *Statistical analysis*

Prism 4.0 (GraphPad Software Inc.) was used to determine discounting parameters (k) for Mazur (1987) hyperbolic discounting model:

$$V = \frac{A}{1 + kD} \qquad (1)$$

In Eq. (1), the term V represents the present value of the consequence. The term, A refers to the amount of the consequence. D is equal to the length of the delay until receipt of the consequence. The term k is a free parameter that indicates the rate at which delayed consequences are discounted.

All indifference points were transformed into present value proportions prior to statistical analysis. For example, an indifference point of \$980.00 would be transformed by dividing by the standard outcome \$1000, producing the present value proportion of .980. Likewise, an indifference point of \$9.80 would be transformed by dividing by the standard outcome \$10.00, producing the present value proportion of .980. In this way, indifference points for \$10 and \$1000 magnitudes could be compared directly.

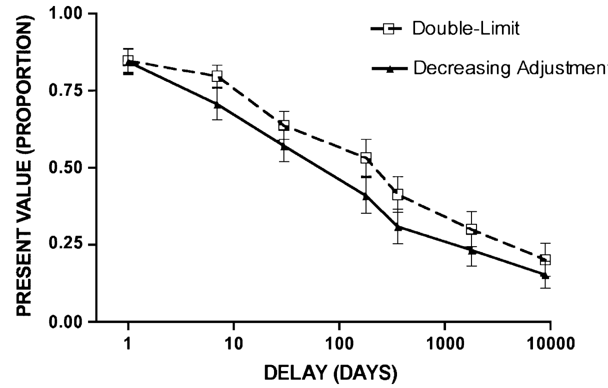

Fig. 1. Mean indifference points (as present value proportions) derived from the Double-Limit and Decreasing Adjustment Algorithms across delays (from 1 day to 25 years) for hypothetical monetary gains (collapsed across \$10 and \$1000 magnitudes). Mean indifference points for the Double-Limit Algorithm are represented by dotted lines and transparent squares. Corresponding data for the Decreasing Adjustment Algorithm are represented by solid lines and filled triangles. Error bars represent the standard error of the mean.

3. Results

3.1. *Algorithm*

Fig. 1 presents mean indifference points (as proportions of present value) from the two algorithms when participants responded for hypothetical monetary gains (\$10 and \$1000). The Decreasing Adjustment Algorithm appeared to produce systematically lower indifference points, indicating greater discounting, than the Double-Limit Algorithm. A repeated measures analysis of variance (ANOVA) comparison of all indifference points (Algorithm [2] × Sign [2], Magnitude [2] × Delay [7], $\alpha = .05$) indicated no statistically significant differences as a function of Algorithm ($F[1,19] = 1.064$, $p > .05$) or Sign ($F[1,19] = 3.015$, $p > .05$). Delay and Magnitude both produced significant main effects ($F[6,114] = 94.287$, $p < .05$ and $F[1,19] = 15.538$, $p < .05$), indicating that as delay increased or magnitude decreased individuals discounted at a greater rate. Post hoc tests indicated that both algorithms were independently capable of detecting significant effects of Magnitude and Delay ($p < .05$). The interaction between Sign and Algorithm was statistically significant ($F[1,19] = 6.773$, $p < .05$), indicating that indifference points generated by the two algorithms should be considered with respect to losses and gains.

3.2. *Sign and Algorithm*

The interaction between Sign and Algorithm was consistent with making comparisons of the two algorithms separately for losses and gains. A repeated measures ANOVA comparing the two algorithms for gains (Algorithm [2] × Magnitude

Table 1
Correlations between discounting parameters derived from each algorithm

Decreasing Adjustment	Double-Limit			
	\$10 gain	\$1000 gain	\$10 loss	\$1000 loss
\$10 gain	.804*	–	–	–
\$1000 gain	.272	.624*	–	–
\$10 loss	.265	.422	.624*	–
\$1000 loss	.460	.566	.410	.616*

* $p < .005$.

[2] × Delay [7]) found higher indifference points were observed with the Double-Limit Algorithm ($\bar{X} = .531$) than for the Decreasing Adjustment Algorithm ($\bar{X} = .463$; $F[1,19] = 9.876$, $p < .05$). Post hoc tests revealed significant differences between indifference points generated by the two algorithms at delays of 1 week, 1 month, 6 months, and 1 year. A repeated measures ANOVA comparing the two algorithms (Algorithm [2] × Magnitude [2] × Delay [7]) for losses did not find statistically significant differences for the main effect of algorithm ($F[1,19] = .608$, $p > .05$).

A repeated measures ANOVA (Sign [2] × Magnitude [2] × Delay [7]) comparison of indifference points from gains and losses was conducted separately for each of the two algorithms. The Decreasing Adjustment Algorithm produced lower indifference points, indicating greater discounting, for gains than loses ($\bar{X} = .463$ and .557, respectively; $F[1,19] = 7.690$, $p < .05$). For the Double-Limit Algorithm average indifference points were nearly identical for gains and losses ($\bar{X} = .531$ and .532, respectively).

3.3. Discounting parameters

Eq. (1) was used to fit indifference points produced by the two algorithms. Because the distribution of the discounting parameter k was skewed, natural logarithm transformations of k ($\ln k$) were used. A repeated measures ANOVA (Algorithm [2] × Magnitude [2]) compared $\ln k$ values from the two algorithms for monetary gains. Results (above) were confirmed, demonstrating greater rates of discounting when using the Decreasing Adjustment Algorithm than when using the Double-Limit Algorithm ($F[1,18] = 6.928$, $p < .05$). Measures of goodness of fit (R^2) by Eq. (1) for data generated by both algorithms were compared using repeated measures ANOVA (Algorithm [2] × Magnitude [2], both as within-subject factors). The main effect of Algorithm did not indicate a statistically significant difference between R^2s from the Double-Limit and Decreasing Adjustment Algorithms ($F[1,18] = .110$, $p > .05$).

Pearson correlations were conducted with $\ln k$ values and results are listed in a correlation matrix (Table 1). Correlations of $\ln k$ values between disparate conditions (e.g., \$10 Gains Double-Limit versus \$1000 Gains Decreasing Adjustment) were weak. Correlations of $\ln k$ values between algorithms in comparable conditions (e.g., \$10 Gains Double-Limit versus \$10 Gains Decreasing Adjustment) indicated a linear relationship (rs between .616 and .804). The strengths of these correlations reveal that variability which could be attributed to differences in the algorithms was small relative to variability which could be attributed to other variables in this study (e.g., Magnitude). Correlations between $\ln k$ values from comparable conditions were statistically significant (ps < .005, $\alpha = .005$), indicating the observed relationship was not likely to be due to chance. Other correlations in Table 1did not reach statistical significance. Note that the alpha level was adjusted using the Bonferroni correction (desired alpha for a single hypothesis test divided by number of tests) for these correlations.

4. Discussion

Indifference points for gains were often higher for the Double-Limit Algorithm than for the Decreasing Adjustment Algorithm. The Decreasing Adjustment Algorithm produced steeper rates of discounting than the Double-Limit Algorithm for gains. Results for losses did not produce statistically significant differences between the two algorithms (in terms of rates of delay discounting). Despite the differences that were found between the algorithms, Mazur (1987) hyperbolic equation accounted for similar amounts of variance in the data produced by the Decreasing Adjustment Algorithm and the Double-Limit Algorithm. Furthermore, strong correlations between estimates of discounting ($\ln k$s) derived from the two algorithms suggest that both algorithms measured the same behavioral process.

Differences in accuracy of indifference point calculation (sensitivity) between the two algorithms or methodological artifacts (carry-over effects) probably did not account for the systematic differences reported above. Post hoc, we determined that differences in sensitivity were not likely to have influenced the results with the following three step process. First, a single indifference point was selected (e.g., \$9.00). Second, responses were made for each procedure that were consistent with the selected indifference point until each algorithm finished and calculated its own indifference point. Third, the calculated indifference points were compared between the two algorithms. Following this three step process, the two algorithms produced nearly identical indifference points. This illustrates that differences in indifference points (reported above) cannot be attributed to differences in the accuracy with which each algorithm calculates indifference points.

Carry-over effects were also a concern in this within-subjects study because the two algorithms were run consecutively (with no planned break). To reduce the possibility of a carry-over effect, the order in which the two algorithms were presented was counterbalanced. However, counterbalancing does not completely eliminate the possibility of carry-over effects influencing within-subjects comparisons (cf. Madden et al., 2004). Post hoc comparisons of $\ln k$ values between the 10 participants that completed the Double-Limit Algorithm first and the 10 participants that completed the Decreasing Adjustment Algorithm first were conducted for hypothetical monetary gains. Despite this limited sample size, the findings of this comparison were consistent with the within-subjects comparisons showing steeper discounting with the Decreasing Adjustment Algorithm. This indicates that carry-over effects, as a potential methodological artifact, did not directly affect the central comparison of this experiment.

A plausible explanation remains for the current results: different levels of effort associated with completing the two algorithms may have occasioned the participants to settle on different amounts of money that would be accepted as immediate gains. Unfortunately, it does not seem clear at this point which algorithm required more effort to complete. However, several variables could be manipulated in future experiments to test this explanation. First, the number of trials in the Decreasing Adjustment Algorithm could be increased to make that algorithm require more effort and to match the average number of trials necessary to complete the Double-Limit Algorithm. The results of this experiment could eliminate the possibility that fewer trials led to steeper rates of discounting in the current experiment. Second, a command box that asks participants to verify their responses, like the one used on the Decreasing Adjustment Algorithm, could be added to the Double-Limit Algorithm. The results of this experiment could eliminate the possibility that a salient verification of each response might make the Double-Limit Algorithm require more effort (by adding the additional deliberation necessary to verify their response). The increased effort required to verify each response could then be ruled out as an explanation for the steeper rates of discounting in the current experiment. Third, random distracter trials could be added to the Decreasing Adjustment Algorithm to make the immediate outcome available on each trial less predictable. The results of this experiment could rule out the possibility that subjectively predictable trials might have made that task require less effort and led to steeper rates of discounting in the current experiment.

The current results correspond well with findings from previous studies that suggest caution when comparing results from different measures of discounting. For instance, Epstein et al. (2003) study, which employed two highly correlated measures of delay discounting, found that a computerized measure resulted in statistically significant gender differences (males discounted at steeper rates than females) while a paper and pencil measure did not. Post hoc analysis of results of the current study indicated that both algorithms found steeper rates of discounting among males than females. However, neither algorithm used in the present study, with a much smaller number of participants than Epstein et al.'s study, found fewer or more statistically significant gender differences in discounting across Sign (losses and gains) or Magnitude ($10 and $1000) conditions.

Finding that discounting measures occasionally produce different outcomes among the same participants does not necessarily present a problem of great significance. As Madden et al. (2004) argued, a small but statistically significant difference in discounting parameters could possibly be detected when comparing real versus hypothetical rewards using large sample sizes. However, small methodologically driven differences may not influence interpretations of group differences. For example, the between-group differences in discounting that are typically seen when making comparisons between heavily addicted participants and controls (see Bickel et al., 1999) are not affected. Comparatively, the differences within participants that were seen across measures of discounting in this study were negligible. Assuredly, different measures of discounting can be fairly compared under certain conditions and in other conditions comparisons should be avoided. A general rule of thumb might be that comparisons between measures of discounting are reasonable when the expected difference from an experimental effect is large enough to outweigh the expected difference from using different measures by an order of magnitude. For example, if the expected difference in median *k*s between groups is .01, then a difference in median *k*s between measures of .001 is acceptable.

If time to complete interactive, computerized discounting assessments is a substantial concern, then the results of the present study suggest that the Decreasing Adjustment Algorithm is superior to the Double-Limit. Because the number of trials for the Double-Limit Algorithm is partially dependent on chance and partially dependent on consistent responding (the number of trials increases as inconsistent responding increases), this algorithm required as few as four but as many as 45 trials to determine a single indifference point (with a mean of 13.86 trials overall) in the gains condition of the present study. In contrast, the number of trials in the Decreasing Adjustment procedure is fixed, requiring six trials to determine every indifference point. This difference is substantial, allowing for faster completion of discounting assessments, or the completion of more assessments in a comparable amount of time, with the Decreasing Adjustment procedure.

Even with this general guide, the task a new experimenter faces in selecting which procedure to use can probably not be settled in a direct empirical fashion. In some instances, a procedure that is more capable of measuring subtle group differences may require a degree of experimental rigor (e.g., experiential discounting) or financing that is beyond the experimenter's resources (e.g., real monetary rewards). If the gold standard cannot be afforded, then researchers must rely on own their creativity and ingenuity to provide reasonable alternatives or to seek related questions that do not require the same costs.

Acknowledgements

This work was funded by NIDA Grant R01 DA11692 and Tobacco Settlement Funds, 2005-2005. The authors would like to thank Casey Pierce for her assistance with collecting data. Additionally, we would like to acknowledge the reviewers and the editor for their helpful comments on a previous version of this manuscript.

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