PNAS

Supporting Information for

Effort Foraging Task reveals positive correlation between individual differences in the cost of cognitive and physical effort in humans

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Supporting Information Text

1. Overall threshold results

We computed the group mean overall exit thresholds separately in Experiments 1 and 2 using mixed effect linear regression using only an intercept term. We compared these observed group overall thresholds to best thresholds from simulations (see group-level means by condition in Fig. S2). We found that the mean exit threshold across all conditions in Experiment 1 was 6.30 apples (SE = 0.11, df = 615.95, t = 56.09, $p < 0.001$). The group average was close to the best threshold identified by simulation (6.78 apples), however individuals varied widely. The group-level mean overall threshold was 4.02 apples in Experiment 2 (SE = 0.22, df = 80.22, t = 18.47, $p < 0.001$) which was close to the best policy in simulation of 4.65 apples. Using linear regression we estimated the mean exit threshold across all conditions ("overall threshold") per participant and included these estimates as an additional dimension of individual differences in the task (when testing the relationship between task behavior and surveys). The overall exit threshold may reflect a relevant individual difference in representations of subjective reward rate and have been hypothesized also to be affected in depression (1, , Fig. S2). A benefit of this task is that it can simultaneously measure exit thresholds and effort costs. Striatal dopamine is hypothesized to represent average reward rate in foraging settings (2, 3). Consistent with this exit thresholds are lower (more over-harvesting) in individuals with Parkinson's (3, 4), when participants are chronically or acutely stressed (5), and in individuals with opioid dependence (6). Critically, high cognitive and physical effort costs are derived from a shift in exit threshold, this partials out the variance having to do with overall threshold.

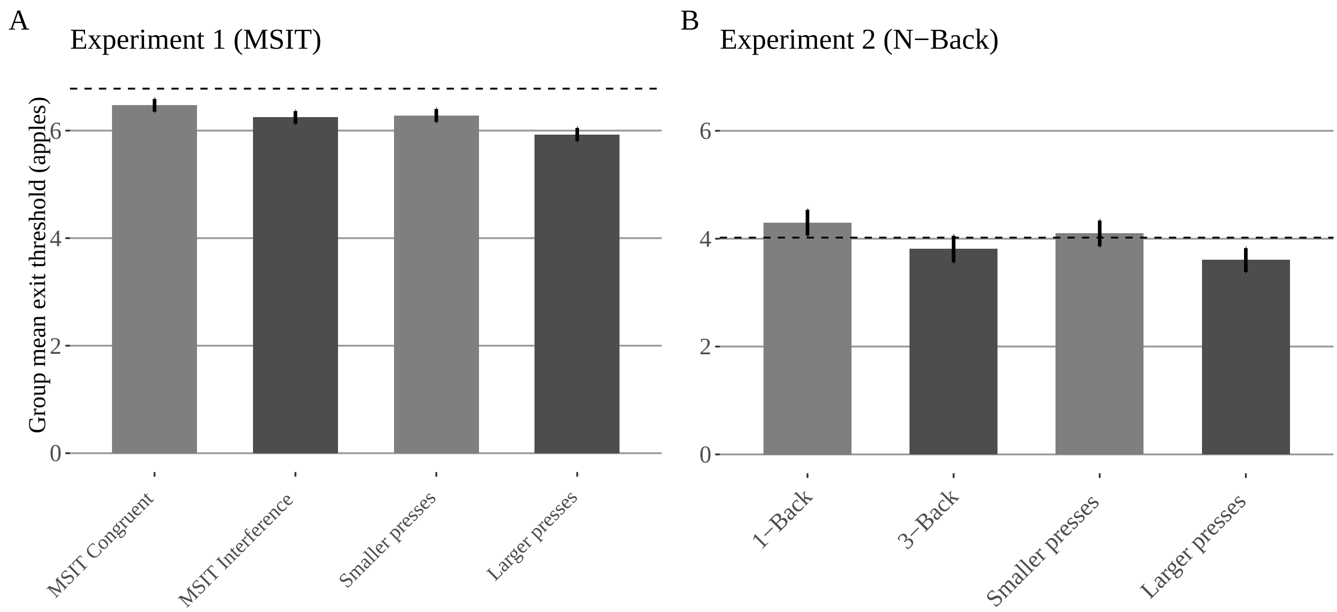

Fig. S1. Group-level exit thresholds Experiment s 1 and 2. A: Experiment 1, B: Experiment 2. x-axis: Foraging conditions indicated by the travel task required, y-axis: Group-level mean exit threshold (apples), error bars indicate SEM. Effort level indicated by bar color (light gray = low effort, dark gray = high effort). Group average thresholds near best threshold from simulation (best threshold respect to reward rate indicated by dotted line, 6.78 apples in Experiment 1 (MSIT), 4.65 apples in Experiment 2 (N-Back)).

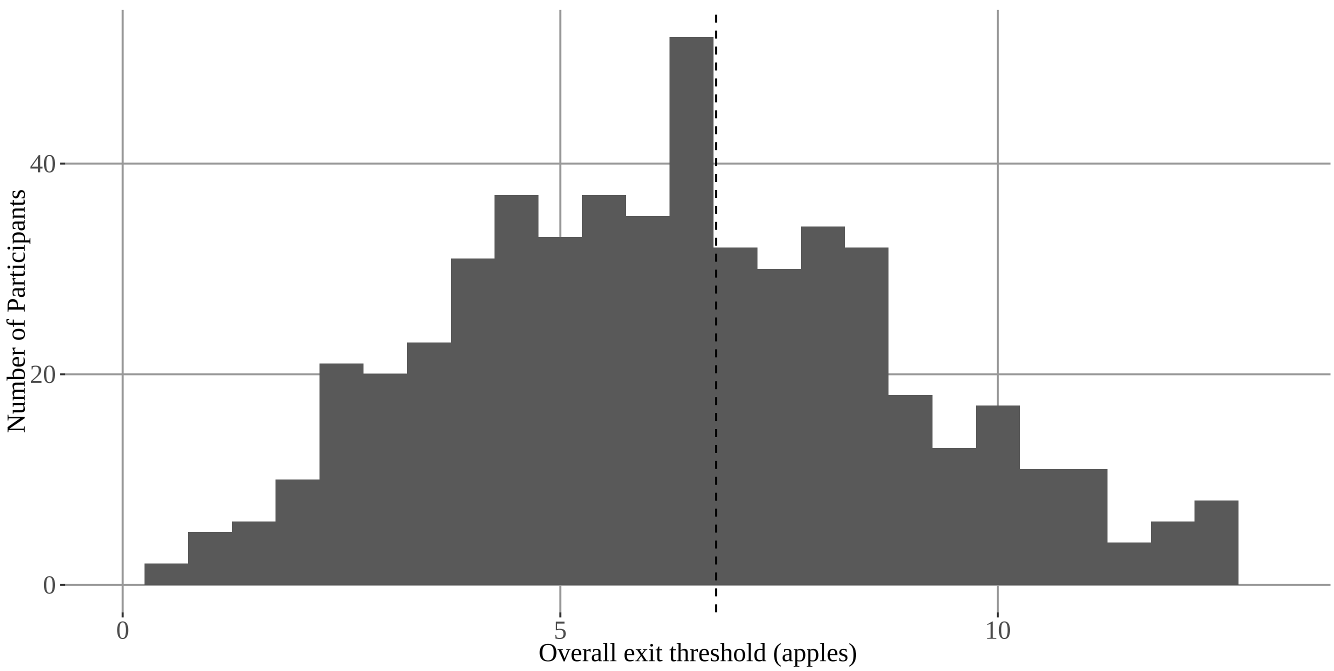

Fig. S2. Individual differences in overall threshold. Experiment 1 histogram of individual differences in mean foraging exit threshold estimated using mixed-effects regression Experiment 1 (MSIT). Some individuals over-harvest (exit threshold below best threshold, dotted line, 6.78 apples) while others under-harvest (exit threshold above best threshold).

Parameter	Mean	Lower bound	Upper bound
Cognitive Effort Cost	7.547	5.472	9.618
Cognitive Low Effort Travel Cost	94.646	90.704	98.746
Physical Effort Cost	13.527	10.903	15.883
Physical Low Effort Travel Cost	99.781	95.399	103.838
Inverse Temperature	0.260	0.239	0.283

Table S1. Group level posterior distributions. The Experiment 1 (MSIT) group level average high cognitive effort cost was 7.5 apples. The group level average high physical effort cost was 13.5 apples. For each parameter (column 1) the table shows the mean of the group-level posterior distribution (column 2) and the 95% highest density interval (lower bound, column 3; upper bound, column 4).

2. Split-half reliability

We computed the split-half reliability of the change in exit threshold measures in Experiment 1 using hierarchical regression modeling following Rouder & Haaf (2019). We took all the exit trials in a single block and split them in half, we adapted the mixed-effects regression model to fit the change in exit threshold separately for the first and second halves, then we examined the random effects correlation of the first and second half change exit threshold. The resulting reliability was r=0.85 for cognitive effort and 0.82 for physical effort.

3. Cognitive and physical effort cost relationship excluding negative effort cost participants.

The consistent observation of participants showing negative effort costs is interesting and opens up a research agenda on effort seeking using this task. However the mechanisms underlying effort seeking remain to be understood. Did negative effort costs reflect value added by effort, boredom aversion, or another unmeasured individual difference? We confirmed that the Experiment 1 finding of a positive correlation between cognitive and physical effort costs was maintained within the effort-avoiding group of participants, by rerunning the MVT model excluding participants with negative cognitive (N=78) or physical (N=67) effort costs (i.e., effort-seekers). This left 428 effort-avoiding (i.e., positive effort cost) participants. The positive correlation between cognitive and physical effort costs was robust to this exclusion of participants exhibiting negative effort costs (Fig. S3, 95% highest density interval is -0.021 to 0.851, mean=0.406, and 94.5% of samples>0).

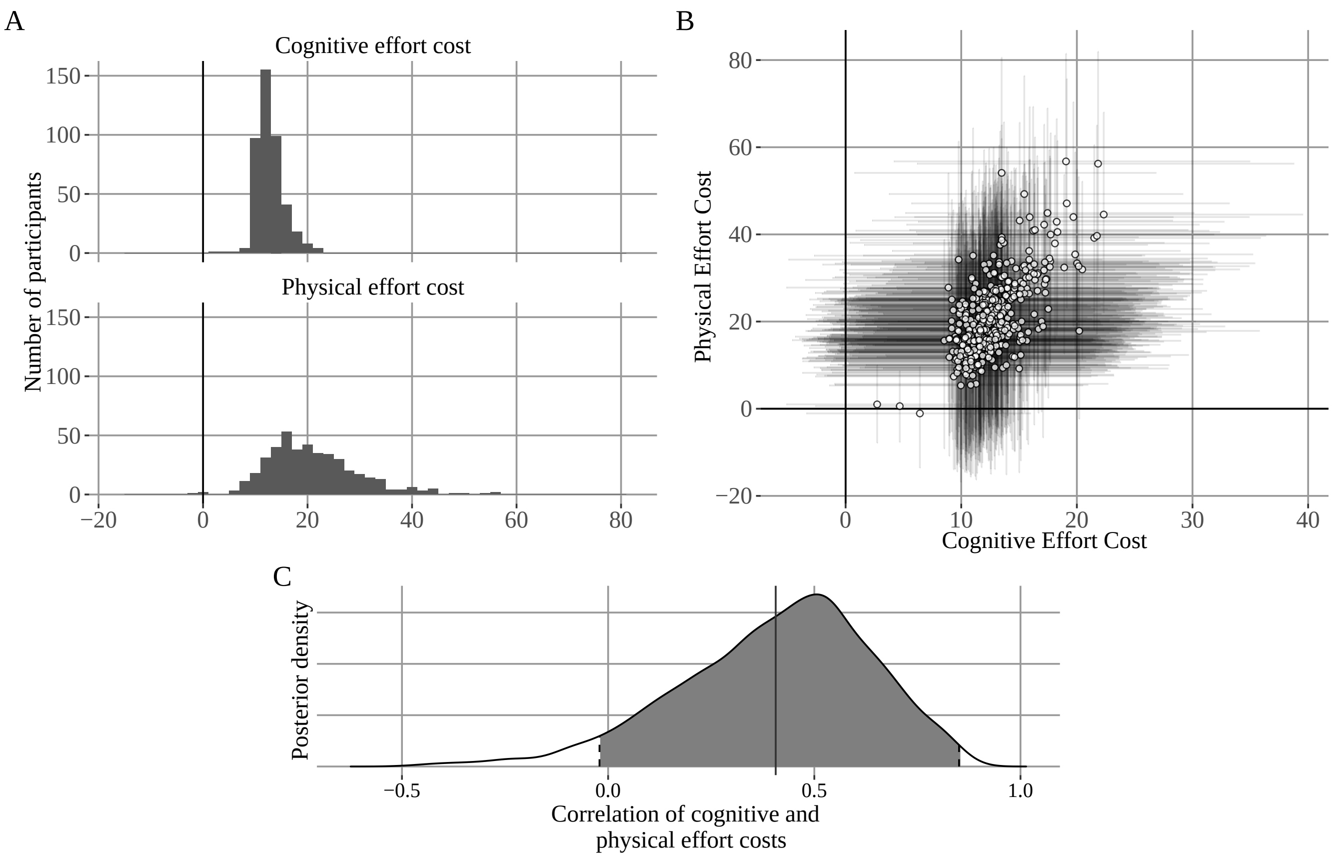

Fig. S3. Cognitive and physical effort cost relationship excluding negative effort cost participants. Experiment 1 correlation between individual differences in cognitive and physical effort costs. A: Individual differences in the high effort travel costs (expressed as the additional cost of the high relative to the low effort condition). Paralleling the pattern of exit thresholds most participants experienced the high effort conditions as effortful (positive cost), whereas some participants were insensitive to the effort manipulation (cost near zero) and others were effort seeking (negative cost). B: x-axis: Individual differences in cognitive effort costs, y-axis: Individual differences in physical effort costs. Error bars indicate 80% HDI. C: posterior distribution of correlation between high effort cost for cognitive and physical effort. Cognitive and physical effort costs are positively correlated.

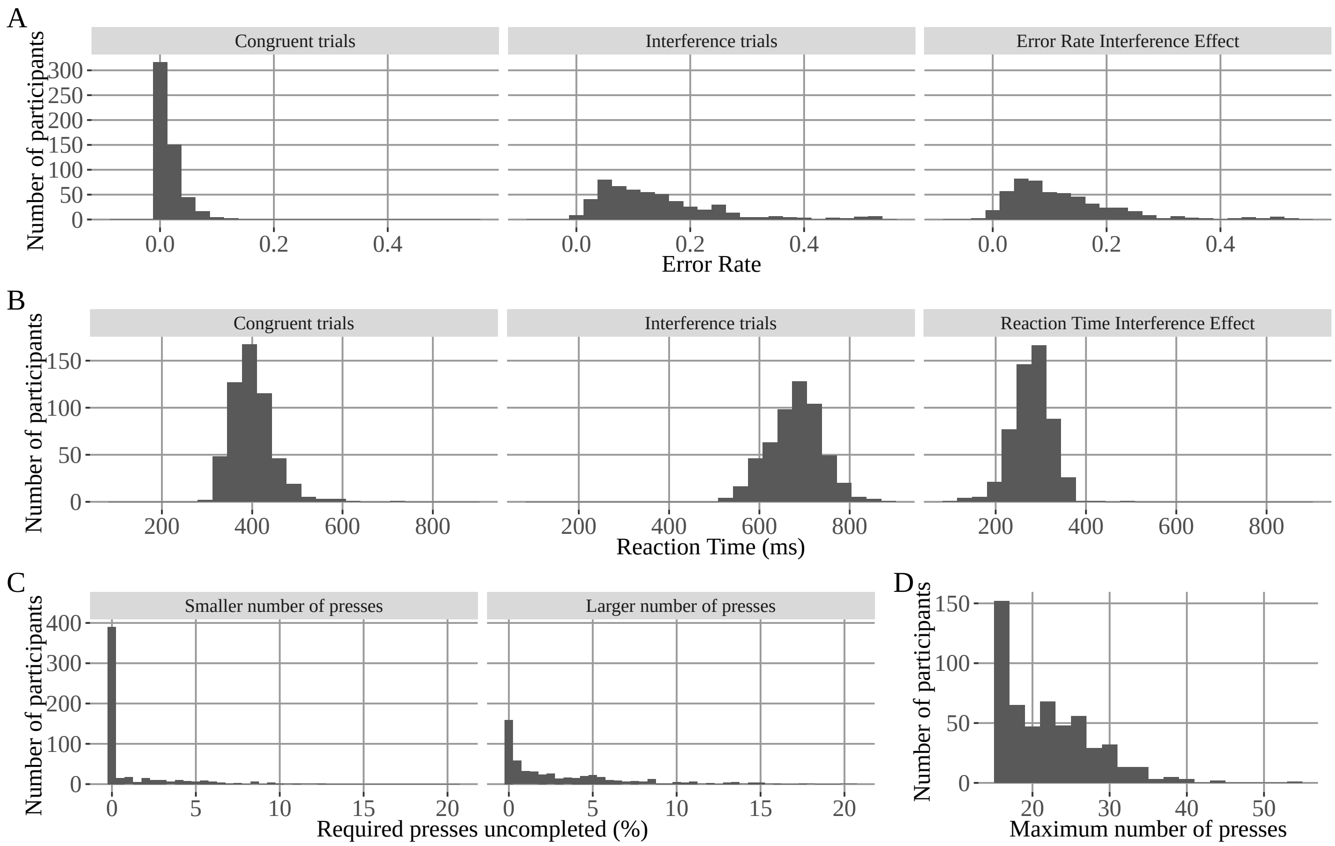

Fig. S4. Individual differences in travel task performance. Histogram of individual differences in travel task performance for Experiment 1 participants (after exclusions). A: Error rate (computed as log(2-correct)), B: Reaction time. Column 1: congruent trials, column 2: interference trials, column 3: interference effect (interference minus congruent). C: Rapid key pressing performance. Column 1: uncompleted smaller number of presses (% of required presses), column 2: uncompleted large number of presses, column 3: maximum number of presses determined in calibration phase (15 presses was set minimum).

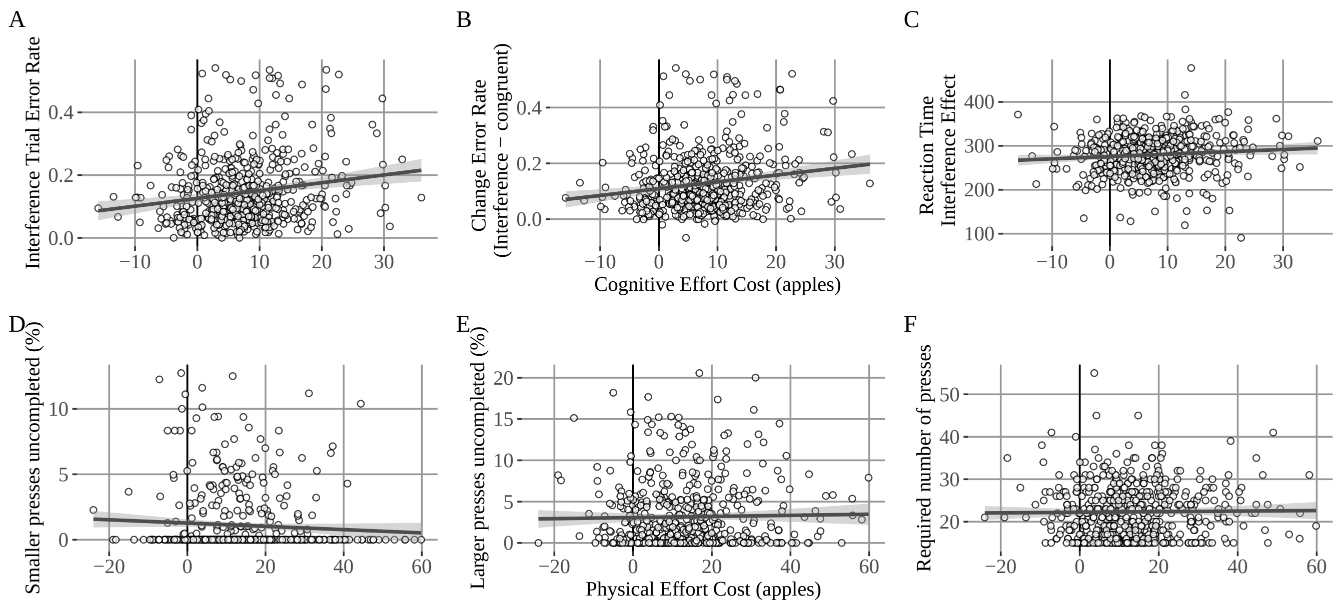

Fig. S5. Relationship between travel task performance and effort costs. Experiment 1 cognitive effort cost positively related to error rate measures but not reaction time interference effect. A: Interference trial error rate (log transformed), B: change in error rate (Interference - Congruent), C: change in reaction time (Interference - Congruent). Physical effort cost not related to rapid keypressing performance. D: percent of smaller presses uncompleted. E: percent of larger presses uncompleted. F: required number of presses determined in calibration phase.

4. Self-report surveys

In Experiment 1 we collected a number of measures of current experience with psychiatric symptoms. The Apathy Motivation Index (7) which measures apathy and motivation in the behavioral, social, and emotional domains and was designed to be suitable for use in the general population. The Snaith–Hamilton Pleasure Scale (SHAPS, 8) measures anhedonia by asking about responses to common domains of pleasure. We administered the Patient Health Questionnaire-9 (PHQ-9, 9), a common measure of depression symptoms, and the Generalized Anxiety Disorder-7, a common measure of anxiety symptoms (10). We administered four scales from the Patient-Reported Outcomes Measurement Information System (PROMIS, 11); the Cognitive Function Short Form 4a, the Cognitive Function Abilities Short Form 4a, Fatigue Short Form 4a, and General Self-Efficacy. Given our particular interest in cognitive function symptoms such as slowed thinking and reduced concentration we used the PROMIS Cognitive Function Short Form 4a which measures subjective cognitive functioning. For this subscale higher scores indicate fewer complaints about recent cognitive function. We also used the complimentary PROMIS Cognitive Function Abilities Short Form 4a, for which higher scores indicate better subjective cognitive function. The combination of these subscales provides a total PROMIS Cognitive Function score for which higher values indicate better recent cognitive function. Lastly, we used the PROMIS Fatigue Short Form 4a to measure physical fatigue symptoms which we hypothesized would be correlated with greater physical effort costs.

In addition to symptom state measures, we also collected several trait measures. To capture self-reported cognitive control capacity, we used the Adult Temperament Questionnaire - Effortful Control scale (12) which had been related to depression in a previous study (13). We also used the Need for Cognition scale (14, 15) which measures the extent to which individuals are prone towards engage in cognitively effortful activities. We predicted a negative relationship between cognitive effort cost and need for cognition given previous reports of such a relationship (16). We collected the Behavioral Inhibition, Behavioral Activation Scales (BIS/BAS, 17) which measure an individuals' sensitivity to the behavioral approach and behavioral avoidance system (abbreviated form 18). This measure was useful for several purposes. Firstly, we used it as a measure of reward sensitivity, in line with evidence linking Behavioral Activation to striatal activation in anticipation of rewards (19). Research also shows Behavioral Activation scores tend to be lower and Behavioral Inhibition scores tend to be higher in more depressed participants (20–24). The theoretical work by Grahek and colleagues (2019; 25) also identified self-efficacy as a potentially relevant factor in cognitive control decision making in depression. By this account more depressed participants may be less likely to predict that exerting effort will lead to a rewarding outcome. We used the PROMIS General Self-Efficacy scale, in which participants respond how confident they are for items such as 'I can manage to solve difficult problems if I try hard enough'. We predicted participants with higher self-efficacy would have a stronger belief that effort will result in reward, potentially leading to a greater propensity to exert effort. Though, ideally this factor would be assessed with a cognitive task that manipulates efficacy (see 26).

A. Self-report attention checks. Infrequent attention check items were embedded in the self-report surveys in Experiment 1 to ensure participants were reading the items (following 27). 28 participants were excluded from self-report analyses (i.e., CCA) because they failed either of the attention check items embedded in the Apathy Motivation Index, and Generalized Anxiety Disorder-7 self-reports (Fig. S6). We did not use the items embedded in PROMIS-Cognitive Function or the Patient Health Questionnaire-9 self-reports because response patterns indicated ambiguity in the questions.

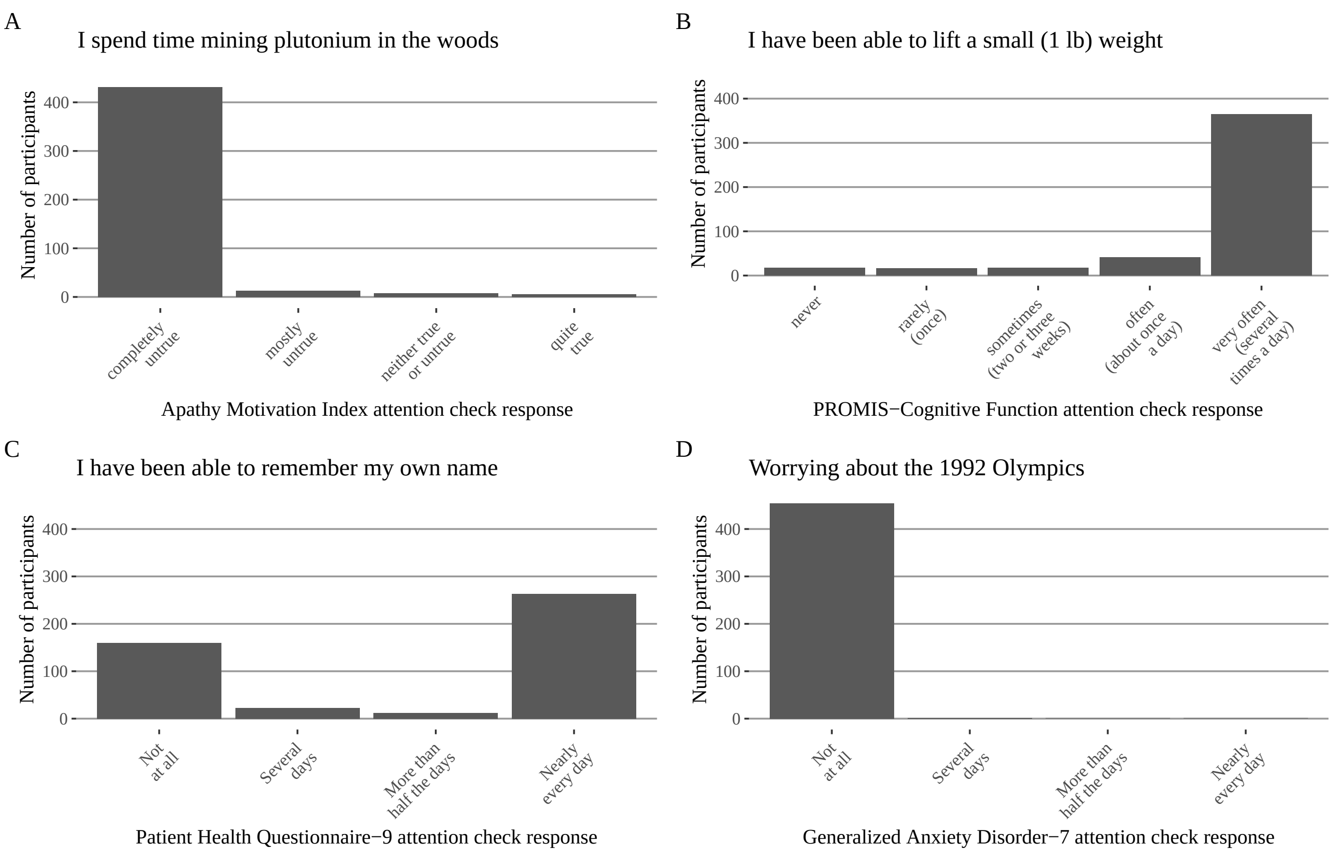

Fig. S6. Attention check items results. A: Apathy Motivation Index, "I spend time mining plutonium in the woods", correct answer "completely untrue". B: PROMIS-Cognitive Function, "I have been able to lift a small (1 lb) weight, correct answer "very often (several times a day)". C: Patient Health Questionnaire-9, "I have been able to remember my own name", correct answer "Nearly every day". D: Generalized Anxiety Disorder-7, "Worrying about the 1992 Olympics", correct answer "Not at all". Experiment 1 participants were excluded if they were inattentive on the Apathy Motivation Index, and Generalized Anxiety Disorder-7 items.

Scale name	N items	Construct measured	Time scale
Patient Health Questionnaire-9	9	Depression	last 2 weeks
Generalized Anxiety Disorder-7	7	Anxiety	last 2 weeks
Apathy Motivation Index	14	Apathy	last 2 weeks
Snaith-Hamilton Pleasure Scale	13	Anhedonia	last few days
PROMIS Cognitive Function Short Form 4a	4	Cognitive Function	last 7 days
PROMIS Cognitive Function Abilities Short Form 4a	4	Cognitive Function	last 7 days
PROMIS Fatigue Short Form 4a	4	Fatigue	last 7 days
PROMIS General Self-Efficacy	4	Self-efficacy	last 7 days
Need for Cognition	18	Need for Cognition	trait
Adult Temperament Questionnaire-Effortful Control	19	Effortful Control	trait
Behavioral Inhibition/Activation Scales - Abbreviated	12	Behavioral Inhibition/Behavioral Activation	trait
Total	108		

Table S2. Self-report survey battery. Column 1: scale name; column 2: number of items; column 3; construct measured and variable name used in the canonical correlation analysis; column 4; timescale of survey instructions, 'trait' indicates surveys about behaviors characteristic of the individual. Experiment 1 self-reports were completed in the order listed in this table. Scales asking about similar timescales were grouped together.

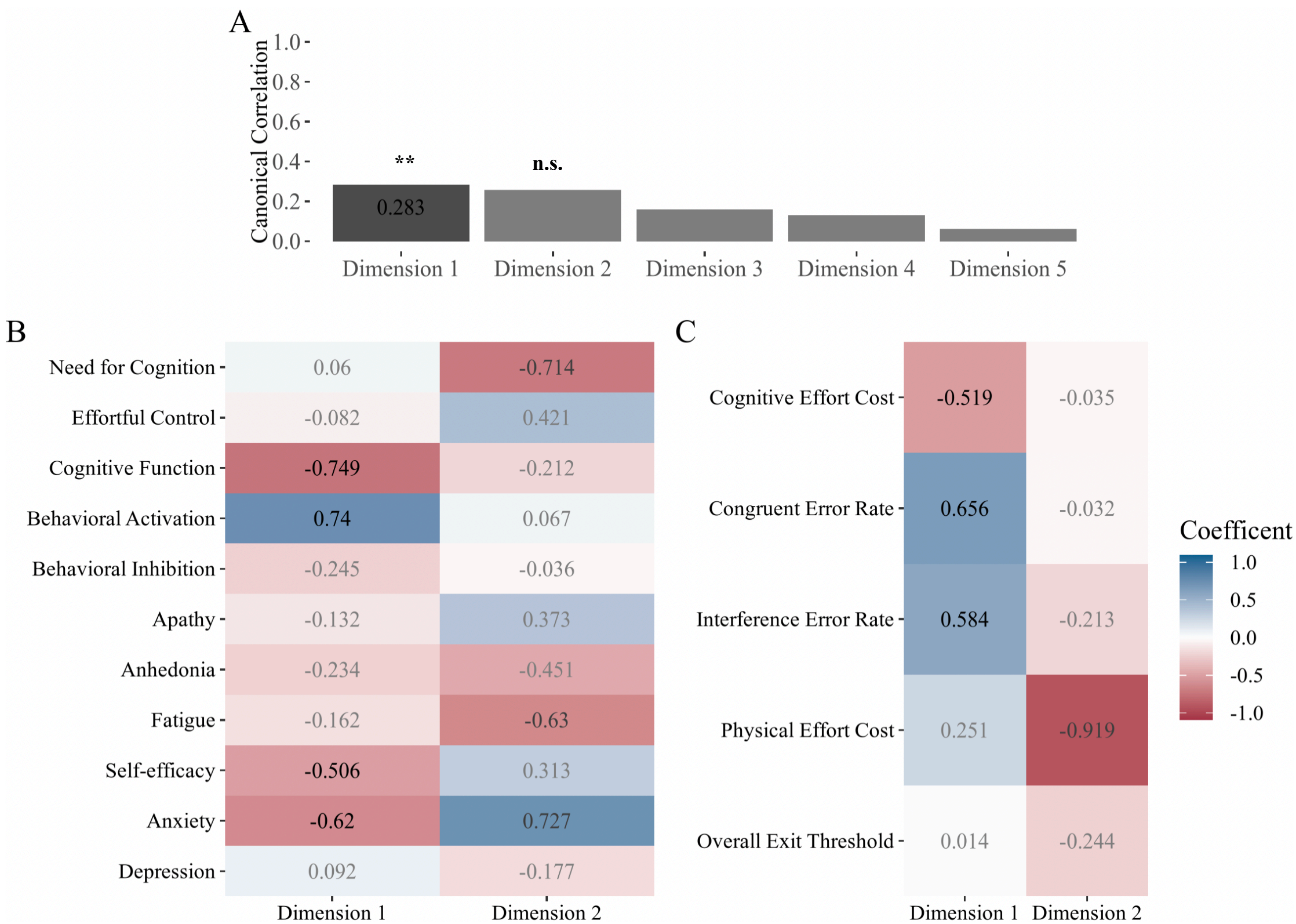

Fig. S7. Experiment 1 full canonical correlation results. A: canonical correlations by dimension. B: dimension coefficients for task parameters (X coefficients). C: dimension coefficients for self-reports (Y coefficients). Coefficients with absolute value larger than 0.5 from significant dimensions are shown in black for the significant dimension and dark gray for non-significant dimension, while coefficients below threshold are shown in light gray. The non-significant second dimension is displayed for completeness.

5. Validation Experiments

A. Experiment 2 (N-Back). We developed two cognitive effort variants of the effort foraging task. In both versions we used a cognitive and a physical effort manipulation. Experiment 2 (N-Back) was developed in an undergraduate population. Experiment 1 (MSIT) was an abbreviated version developed for a large-scale online study. This tested the generalizability of the task in terms of population as well as in the type of cognitive effort (working memory versus inhibition).

A.1. Participants. 116 Undergraduate students volunteered for a 2.5-hour self-guided remote experiment (Experiment 2 (N-Back), 18-27 years, mean=20 years ± 1.5, 70 female, 42 male, 4 prefer not to answer). The study was approved by the Princeton University Institutional Review Board and participants were recruited from a pool maintained by the Princeton Psychology Department. Undergraduate students were compensated with 2.5 psychology course credit hours and a performance bonus up to $10 in the form of an Amazon gift card (bonus mean=$7.68, SD=0.61, range=$4.41 - 8.35). The conversion of apples to money was 0.11 cents per apple. Participants were excluded from analysis based on their behavior in the task (Tab. S3).

A.2. N-Back working memory task. The N-Back task was performed as part of foraging task during travel between trees. In the N-Back task letters are displayed on screen in a sequence. Participants judged whether the stimulus that is currently on the screen matches the stimulus they saw a number of screens back (N-Back). On every trial, participants responded whether the letter was a match ("s" key) or non-match ("d" key) to the letter on the previous screen (1-Back case) or three screens before (3-Back case). A trial began with a fixation cross (for 250 milliseconds) followed by the letter on screen (for 500 milliseconds) followed by a blank screen (for 950 milliseconds, total trial duration = 1.7 seconds). During the travel period, 10 letters were presented, of which, 2 or 3 were targets (letter matches letter N-Back) and 2 or 3 were lures (matches current letter but not in position N-Back). The number of targets and lures were selected randomly each time an N-Back stimulus sequence was generated. We only used consonants to prevent participants from using mnemonics (letters were: 'B', 'C', 'D', 'F', 'G', 'H', 'J', 'K', 'M', 'N', 'P', 'Q', 'R', 'S', 'T', 'V', 'W', 'X', 'Y', 'Z'), and half of the letters were presented in upper case and the other half lower case to prevent participants using iconic memory (28).

A.3. N-Back working memory task training. We trained the N-Back task extensively to try to bring participants to highest possible levels of performance and minimize automaticity differences (in which some participants would have more experience with the N-Back or similar tasks, making the task less effortful for them compared to someone with little experience). Participants had to reach a performance criterion to move on from training. After being instructed on the task participants began practice for one of the effort levels (counterbalanced). First, they completed two extended blocks (50 trials with a self-paced break up to 45 seconds between) with feedback about error type (types of feedback: "non-match", "missed match", "no response", displayed in red font for 800 ms after the trial). Then they performed one extended block without any feedback (50 trials).

We tasked participants with completing a set number of mini-blocks with high accuracy to begin the foraging task. We did so to establish the expectation that participants had to exert effort when they chose to travel while foraging. A mini-block was classified as successful when the participant saw no error feedback (large black dot), after which they were told they were moving on to the next mini-block. The error feedback was displayed when participants made two consecutive errors (including omission errors). If they did see one or more error feedback symbols, they had to repeat that mini-block. They had to successfully complete 8 mini-blocks of the 1-Back task, and 12 mini-blocks of the 3-Back task. This training also ensured that participants could adequately perform the task. Participants had self-paced breaks in between mini-blocks (up to 60 seconds).

A.4. No relationship between cognitive and physical effort cost in Experiment 2. In the larger online sample, we found a significant positive correlation between cognitive and physical effort costs (Experiment 1 (MSIT), N=537, correlation=0.55). In the smaller Experiment 2 (N-Back) (N=81) sample we did not find conclusive evidence for or against the correlation, as the highest density interval (HDI) was very wide (Fig. S8, mean correlation=0.048, 95% HDI=-0.369 - 0.462). One explanation is that we were underpowered to detect a correlation similar in size to that seen in Experiment 1. Encouragingly, the HDI for the Experiment 2 (N-Back) model overlapped with the HDI in Experiment 1 (MSIT). Another difference between experiments is that Experiment 2 is an undergraduate student population, while Experiment 1 might more closely reflect the general population. We speculated that, with respect to our experimental question 'are cognitive and physical effort cost correlated?', there may be a selection bias due to conditioning on a collider in Experiment 2. The collider would be admission to university (a classic example 29), which may select for students specializing in either academics (cognitive effort) and not athletics (physical effort) or vice versa. This negative correlation induced in this population between academic and athletic ability may tend to cancel out the positive correlation demonstrated in Experiment 1. This could be tested in a larger population of undergraduates sufficient to confidently detect the presence or absence of a correlation.

A.5. Explicit awareness of effort avoidance. In Experiment 2 (N-Back), we asked participants if, and how, the required travel task changed their decision to travel to a new tree. For the cognitive (N-Back) variant, of those who completed the debrief survey (N=113), 36% of participants (N=41) reported changing their behavior based on the travel task (saying in their own words that they avoided the high cognitive effort [3-Back] task and stayed longer at a tree), whereas 64% of participants (N=72) explicitly stated that the travel task did not change their decisions. This supports the idea that the task is an indirect measure for the majority of participants (i.e., participants whose behavior was influenced by the travel task were not aware of doing so).

A.6. Effort ratings. We asked participants to rate how effortful each of the travel tasks was. For Experiment 2 (N-Back), 9 participants reported no change in effort rating between high and low cognitive effort, 2 participants reported the low effort task as more effortful, and the remaining 102 participants rated the high effort task as more effortful. For Experiment 2 (N-Back), 17 participants reported no change in effort rating between high and low physical effort, 1 participant found the low effort task (smaller presses) to be more effortful, and the remaining 95 participants reported the high effort task (larger presses) was more effortful. On average, effort ratings were higher for the 3-Back than the 1-Back task (paired two-tailed t-test, mean of the differences=1.99, t=19, df=112, $p<0.001$). Participants also found the larger button presses condition to be more effortful than the smaller presses on average (mean of the differences=1.48, t=15.42, df=112, $p<0.001$).

Exclusion criteria	N outlier participants	Cutoff	Mean, SD
Did not complete experiment	9		
Foraging trial response deadline missed (> 10% trials)	7	10	(4.933, 13.893)
1-Back accuracy (D', < 2SD)	5	1.723	3.070, 0.675
3-Back accuracy (D', < 2SD)	5	0.665	2.260, 0.796
Smaller number of presses uncompleted (%, >2SD)	9	2.827	0.4428, 1.192
Larger number of presses uncompleted (%, >2SD)	5	8.213	1.777, 3.218
Number of exit trials per condition (<2SD)	12	8.268	17.767, 4.749
Change exit threshold cognitive (apples, <2SD | >2SD)	5	(<-3.1145 | >1.967)	-0.574, 1.270
Change exit threshold physical (apples, <2SD | >2SD)	6	<-2.964 | >1.725	-0.619, 1.172
Initial Sample Size	116		
Final Sample Size	81		

Table S3. Experiment 2 (N-Back) Exclusion Methods. Column 1: basis of exclusion, column 2: numbers of outlier participants for Experiment 2 (N-Back), column 3: exclusion cutoff value. Participants could be excluded on multiple grounds, therefore the number of outlier participants listed are do not reflect the total number of excluded participants (shown in the bottom two rows).

Parameter	Mean	Lower bound	Upper bound
Inverse Temperature	0.425	0.383	0.469
Cognitive Low Effort Travel Cost	114.909	105.088	125.274
Cognitive Effort Cost	16.776	10.356	23.441
Physical Low Effort Travel Cost	124.295	112.371	136.350
Physical Effort Cost	15.943	8.915	23.007

Table S4. Experiment 2 (N-Back) Parameter posterior distribution values. Table includes the mean of the group-level posterior distribution and the upper and lower bounds (95% HDI).

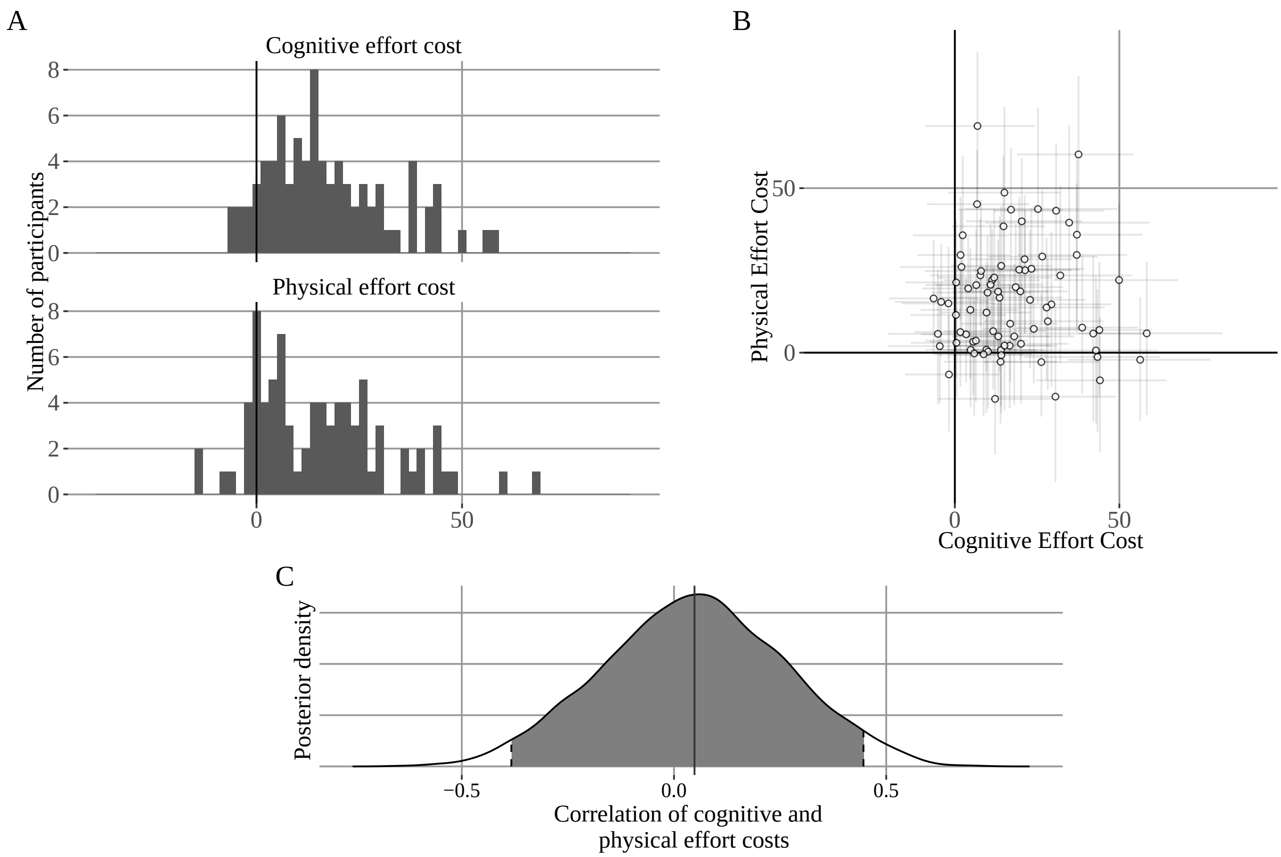

Fig. S8. Experiment 2 (N-Back) individual differences in effort costs. A: There were individual differences in cognitive (3-Back) and physical high effort cost. Some participants were insensitive to the manipulation (cost near zero). B: cognitive versus physical effort cost relationship, error bars represent 80% HDI. C: posterior distribution of correlation between high effort cost for cognitive and physical effort. No correlation between cognitive and physical effort cost, wide confidence interval (shaded area represents 95% HDI) suggests sample is underpowered to detect a correlation similar in size to Experiment 1.

B. Experiment 3 (Richness).

B.1. Methods. In Experiment 3 (Richness) we conducted a study manipulating the tree richness as a benchmark of how participants adjust their exit threshold in response to reward rate (richness was not manipulated in Experiments 1 and 2). We compared two levels of reward richness by adjusting the mean of a normal distribution used to draw the initial reward paid out by a tree. In the 'lean condition' the initial reward mean was 15 apples $N(15, 1)$ and in the 'rich condition' the initial reward mean was 20 apples $N(20, 1)$. We tested all combinations of the effort and richness orchard types and counterbalanced block order within effort type. We predicted participants would lower their threshold (exit later) in the lean condition because reward rate is lower in the lean compared to the rich condition. This would confirm that participants still adhere to predictions of the Marginal Value Theorem even in our novel experiment context where effort was added to the travel.

The richness manipulation was conducted during piloting studies of physical effort version of the Effort Foraging Task. There were several differences between the pilot studies (Experiment 3) and the main experiments (1 and 2). Pilot studies were conducted in the laboratory (rather than remotely). For pilot studies we pre-screened participants to have relatively low Need for Cognition (we did not do so in Experiments 1, 2, or 4). The pre-screen survey was completed online no later than 24 hours before the study. Participants gave written consent to complete the pre-screen. To avoid explicit cueing of the objective of the study we administered two foil self-report scales following the Need for Cognition scale: the Individualism and Collectivism Scale (30) and the Ambiguity Tolerance Scale (31). Participants with Need for Cognition scores less than or equal to 70 points (out of 90 possible points) were invited to the study. Participants again gave written consent to participate in the study.

43 participants volunteered for Experiment 3 (Richness) (24 female, 19 male, 18-34 years old, mean age = 21.5 years $\pm$ 3.7). Experiment 3 (Richness) includes two pilot studies in which richness was manipulated. Because of the heterogeneity of methods, we did not fit the MVT model or estimate the relationship between cognitive and physical effort cost in Experiment 3. In the 'button-pressing rate' version, participants had to maintain a fixed rate (smaller number of presses per second vs. larger number of presses per second). In the 'button-press count' version, participants had to complete a smaller number or larger number of their maximum calibrated presses (this was the same physical effort requirement as in the main experiments). The cognitive effort requirement in both versions was the N-Back task (same as in Experiment 2 (N-Back)). There were 21 participants in button-pressing rate version and 19 participants in button-pressing count version. Three participants were excluded due to poor button pressing performance ($>$ 2SD uncompleted presses). In both versions participants completed 4 N-Back blocks followed by 4 rapid button pressing blocks. Orchard duration was 5 minutes in the button-press rate version, and 7 minutes in the button-press count version. Harvest and travel time were the same for Experiments 1 (N-Back) and 3 (Richness).

B.2. Analysis methods. To test whether participants responded as predicted to the richness manipulation, we fitted a mixed-effects linear regression model to exit thresholds (using the lme4 package in the R language, 32). The model predicted exit threshold (expected (log) apples) by orchard type separately fit for all conditions (for cognitive high and low effort, and physical high and low effort, and scarce and rich orchards) for all participants. Then we computed a multi degrees-of-freedom test on the linear mixed-effects model (using contestMD function of the lmerTest package (33)). The contrast tested whether the mean-value parameters are significantly different in the scarce compared to the rich condition (collapsing over all the different travel tasks).

C. Experiment 4 (Instruct fixed travel time).

C.1. Methods. To evaluate whether subjective time may have been a confounding driver of effort avoidance in this task, we conducted an additional 'Experiment 4', in which we explicitly instructed participants that the travel time was fixed between effort levels and quizzed them on this fact. This was a replication of Experiment 1 with the only difference being the addition of explicit instructions that the travel time was fixed across all conditions. 71 Prolific participants volunteered for the study (37 females, 30 males, 4 prefer not to answer, mean age 36.27 years $\pm$ 10.56, range 19-62 years). We applied the exclusion cutoffs from Experiment 1 (Tab. S8) resulting in 54 participants included in analyses.

The instructions added were:

'The time it takes to get to a new tree is fixed. It is NOT RELATED to which orchard you are in or whether you are completing the [matching/small presses] or [mismatching/large presses] trials.'

'You will visit 4 orchards and spend 16 minutes total. Your choices in the game will NOT make the experiment end earlier. Remember, every apple you harvest earns you money! You can earn up to $2 harvesting the Oddball Numbers Apples Game orchards.'

We also added a quiz question that participants needed to answer correctly (correct answer in bold) to begin the experiment:

'Question: What determines how long it takes to travel to a new tree?

Options:

The background color.

The time is fixed.

Whether you are completing matching or mismatching trials of the Oddball Number Game./Whether you are completing the small or large presses of the Button Pressing Game.'

C.2. Analysis methods. To test whether participants still changed their threshold in the high relative to low effort task, we fitted a mixed-effects linear regression model to exit thresholds (using the lme4 package in the R language, 32). The model predicted exit threshold (expected (log) apples) by orchard type separately fit for all conditions (for cognitive high and low effort, and physical high and low effort) for all participants. Then we computed a multi degrees-of-freedom test on the linear mixed-effects model (using the contestMD function of the lmerTest package, 33). We found a significant decrease in exit threshold, replicating Experiment 1 even when participants were explicitly instructed the travel time is fixed (linear mixed-effects regression estimate for MSIT (Interference-Congruent):= -0.318 apples, df=49.50, F=12.66, $p<0.001$, physical (smaller-larger) = -0.391, df=47.72, F=5.66, $p<0.021$, Fig. S9).

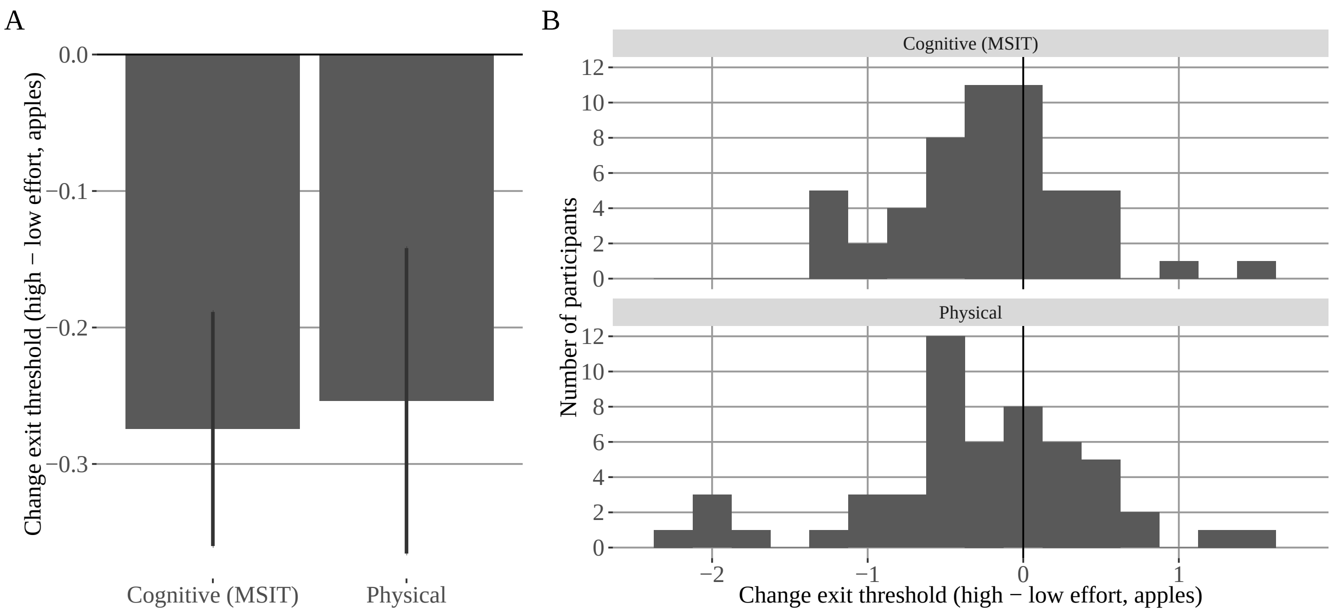

Fig. S9. Experiment 4 (Instruct fixed time), participants avoid effort when explicitly instructed that the travel time is fixed across all conditions. A: y-axis indicates change in exit threshold for cognitive and physical effort (high - low effort level), x-axis indicates effort type, B: histogram of individual differences in change in exit threshold by effort condition, top row cognitive effort, bottom row physical effort.

Parameter	Experiments 1 & 4 (MSIT)	Experiment 2 (N-Back)	Experiment 3 (Richness)
Harvest time	2 seconds	2 seconds	2 seconds
Travel time	8.33 seconds	20 seconds	20 seconds
Cognitive Travel Tasks	MSIT Congruent, Interference	1-Back, 3-Back	1-Back, 3-Back
Physical Travel Tasks	Larger (100% max), Smaller (50%) number of presses	(100% and 50% max)	Number or rate of presses
Block duration	4 minutes	7 minutes	7 minutes
Number blocks per condition	2	2	2
Initial reward	$\mathcal{N}(15, 1)$	$\mathcal{N}(15, 1)$	$\mathcal{N}(15, 1), \mathcal{N}(20, 1)$
Decay rate	β(14.13, 2.03)	β(14.13, 2.03)	β(14.13, 2.03)
Total Number of blocks	8	8	8

Table S5. Foraging environment parameters comparison chart. Column 1: environment parameter for; column 2: Experiments 1 & 4 (MSIT), column 3: Experiment 2 (N-Back), column 4: Experiment 3 (Richness) Experiment 1 (MSIT). Third column: Experiment 2 (N-Back).

Race	Number of participants
American Indian/Alaskan Native	2
Asian	22
Asian & White	2
Black or African American	55
Black or African American & Asian	1
Black or African American & White	3
White	516
White & More than one race	9
More than one race	36
Prefer not to answer	32
Hispanic or Latino	
Hispanic or Latino	119
Not Hispanic or Latino	543
Prefer not to answer	16

Table S6. Experiment 1 Race and Hispanic or Latino ethnicity. Participants reported their race and Hispanic or Latino ethnicity from a multiple choice table. The left column indicates their first selection, the middle column indicates their second selection (if any). The right column indicates the number of participants.

6. Simulation to find best threshold.

We simulated the best foraging threshold by creating a foraging environment with an agent with a fixed exit threshold and observing the resulting reward rate. We used a policy iteration algorithm to find the maximal reward rate for a given foraging environment. The foraging environment was defined by the following parameters from our experiments; the harvest time (2 seconds), travel time (8.33 seconds), the distribution of initial rewards to a tree $N(15, 1)$ distribution of the decay function (beta distribution, $\beta(14.90873, 2.033008)$). We assumed the agent knew the mean depletion rate (0.88 multiplied by the previous reward) and used this value to predict the expected reward on the current trial. If the predicted reward was less than or equal to the agent's threshold it exited the patch $R_e \leq \rho$, otherwise it harvested the patch which yielded reward. We simulated 840 'seconds' of foraging time for all experiments (though the result should be robust to duration). The simulation outputs were the 'best threshold' (threshold that yielded the highest reward rate, results vary slightly by simulation run), the resulting 'best reward rate', as well as the mean and standard deviation number of harvests to reach that exit threshold.

The agents' threshold parameter was initialized at 4 apples. For an iteration i, the threshold was set as the mean reward rate observed in iteration i-1, this allowed the threshold to gradually improve in terms of reward rate between iterations. The simulation stopped and the best threshold was determined based on the stopping threshold of a 0.001 apple per second improvement in reward rate on iteration i compared iteration i-1 (with a maximum of 200 iterations). Best exit threshold policy in simulated data (not including effort costs) was 6.78 apples, the reward rate achieved with best threshold was 3.39 apples per second, and on average it took 6.77 ± 1.69 harvests to reach the best threshold (Tab. S7).

	Exp. 1 & 4	Exp. 2 & 3 (Scarce)	Exp. 3 (Rich)
Best threshold (apples)	6.78	4.65	6.17
Reward rate (apples/second)	3.39	2.32	2.37
Number of harvests (μ)	6.77	9.95	9
Number of harvests (SD)	1.69	2.01	2.56

Table S7. Best exit threshold policy in simulated data. Column 1: best exit threshold policy parameters; column 2: Experiments 1 & 4 (MSIT); column 3: Experiment 2 (N-Back) and Experiment 3 (Scarce condition); column 4 (Rich condition). Row 1: best threshold from simulation (apples); row 2: reward rate achieved with best threshold (apples per second); row 3: mean harvests it took to reach the best threshold; row 4: standard deviation of harvests it took to reach the best threshold.

7. Exclusions Experiment 1.

Experiment 1 participants were excluded if they missed many harvest trials (if they did not respond after 1 second deadline in greater than 10% of all harvest trials). Participants were excluded if they performed poorly on any of the travel tasks (using the metrics MSIT congruent and interference trial error rate, percent smaller presses uncompleted, percent larger presses uncompleted). For each travel task we computed the group mean and standard deviation, and excluded participants who were 2 standard deviations below the group mean performance (Tab. S8).

Exclusion criteria	N outliers	Cutoff	Mean, SD
Did not complete experiment	5		
Foraging trial response deadline missed (% trials)	30	10	2.8, 5.9
MSIT Congruent error rate ($>$ 2SD)	10	16.6	2.7, 7.0
MSIT Interference error rate ($>$ 2SD)	51	54.2	19.2, 17.5
Smaller number of presses uncompleted (%,$>$2SD)	12	14.1	1.9, 6.1
Larger number of presses uncompleted (%,$>$2SD)	29	21.0	4.9, 8.0
Number of exit trials per condition ($<$2SD)	11	5.4	18.6, 6.6
Change exit threshold cognitive ($<$2SD $\mid$ $>$2SD)	30	$<$-2.52 $\mid$ $>$1.91	-0.31, 1.11
Change exit threshold physical ($<$2SD $\mid$ $>$2SD)	31	$<$-2.77 $\mid$ $>$2.0	-0.39, 1.19
Initial Sample Size	678		
Final Sample Size	537		

Table S8. Effort Foraging Task Behavior Based Exclusions Experiment 1. Column 1: basis of exclusion, column 2: number of participants, column 3: exclusion cutoff value, column 4: group mean and standard deviation. Number of participants outliers by exclusion criteria. Participants could be excluded on multiple grounds; therefore, the number of outlier participants does not add up to the number of total number of excluded participants.

8. Foraging task training

In Experiment 1 the task began with training the travel task for the first effort cost variant for a particular participant (this could be the cognitive or physical effort task). Next came instructions for the foraging task in general (without mentioning the effortful travel requirement), and participants completed a practice block (90 seconds) of the foraging task with no travel task. Then participants were instructed that they would have to complete the effortful travel task when traveling, and they completed two practice blocks (one per effort level, 90 seconds each). Then, participants completed the main foraging task for the first travel task type (4 blocks, 4 minutes per block, with self-paced breaks between blocks). After completing all the blocks of the first travel task, participants began training on the second travel task. They were instructed that they would continue to play the foraging task, but the travel task had changed. They practiced the foraging task with the second travel task type (one practice block per effort level, 90 seconds each). Finally, they completed the main foraging task for the second travel task type (4 blocks, 4 minutes per block).

9. Rapid key-pressing task training

In Experiment 1 key-press training began with a calibration phase (three rounds) to determine the maximum number of presses participants were able to complete in the travel time (7.5 seconds of effort task time). A counter was displayed on the center of the screen showing how many presses a participant had made. The instructions suggested participants were being compared to others, and encouraged them to press as fast as possible, each round they were encouraged to press faster than they had the previous rounds (see instructions in SI Text 11). Then we used each participant's mean number of presses across rounds as their 'maximum number'. We enforced a minimum 'maximum number' value of 15 presses. The Larger Number of Presses condition tasked participants with completing 100% of their maximum, and the Smaller Number of Presses condition tasked participants with completing 50% of their maximum. Participants were told that there was a larger and smaller number, but not what that number was or how it was determined. Then participants practiced a single effort level. Effort level order was counterbalanced. Practice for an effort level began with a single mini-block the duration of the foraging travel time. Then participants had to complete 5 mini-blocks reaching the required number of presses to move on. This was meant to establish the expectation that participants would perform well on the travel task, even though there were no incentives or punishments associated with travel task performance during the foraging task.

10. Experiment 1 additional methods

To indicate the start of a trial a circle below the tree turned white and participants were able to make their decision. The circle below the tree was brown when participants could not enter a decision (apples being displayed and waiting through harvest delay). If participants took too long to decide (1 second deadline) a message "Too slow" appeared, after which they waited the harvest delay (2 seconds total). Participants were instructed that more "too slow" messages would result in fewer apples earned. When participants harvested the patch, apples appeared on the screen for 1 second. Regardless of the reaction time, the total harvest delay was always 2 seconds long. When the participant decided to exit, the avatar character moved from the center of the screen rightwards away from the tree until it went off the screen (415 millisecond animation) then the travel task occupied the screen (7.5 seconds), after which the avatar reappeared from the left side of the screen and moved rightwards towards the tree at the center of the screen (415 millisecond animation).

During the task participants were instructed they could look to the background color to know which travel task condition they were in. The background colors were light blue for cognitive low effort, light orange for cognitive high effort, light purple for physical low effort, light green for physical high effort.

The MSIT trials began with 250 ms fixation cross, then the stimulus appeared for 1000 ms and participants could enter their response. After a total of 1250 ms the trial ended. For the MSIT training participants were required to successfully complete 5 mini-blocks of each effort level. Participants were instructed they had to repeat a mini-block if they a black dot was displayed. The black dot indicated that they made two errors in a row, and was displayed for 250ms instead of the fixation cross.

For the rapid key-pressing task participants had to hold the keys 'w', 'e', and 'f' keys with their left hand, and the 'h' and 'o' with their right hand. To minimize cognitive demands the hold keys were always displayed at the bottom of the screen during the rapid key-pressing task. For the rapid key-pressing task training participants had to meet their goal number of presses for 5 mini-blocks per effort level. If they failed to meet their goal number of presses a black dot was displayed and they repeated the mini-block.

11. Foraging task instructions

"Welcome to the experiment! Thank you for participating. This experiment will require you to press buttons on your keyboard repeatedly, applying varying amounts of physical effort. If you have any history of any sort of hand injury or pain with typing (e.g., which could make either fast button pressing or stretching your hand uncomfortable) please do not complete this task. You must wait a minimum of 5 seconds before you are able to progress to a new slide of instructions. You will know you can click to a new slide when the "Next" button changes."

"Welcome to the Apples Game! For your completion of this task, you will receive a potential bonus between $0 and $5. Please read the instructions carefully. There will be a quiz at the end of these instructions to check your understanding. In this game, you will make choices that earn you money. Imagine you are a farmer, and you are harvesting apples from trees in your multiple orchards. On every trial within an orchard, you will see a tree: To HARVEST the tree, press the down arrow key with your right hand. Do this when the circle below the tree is white. When you harvest the tree it gives you apples. These apples are worth real money that you will earn on top of the money for participating in this study. Now, try harvesting the tree three times in a row. Press the HARVEST key to collect apples from the tree. [Press "Next" to practice using the HARVEST key 3x]"

"The more times you harvest a tree, the fewer apples it gives you! On any trial, instead of accepting the number of apples the tree is giving you, you have the option to TRAVEL to a new tree. To TRAVEL to a new tree press the right arrow key with your right hand. Do this when the circle below the tree is white. Now, harvest the tree once and travel from one tree to another. Do this three times. Press the TRAVEL key to move to a new tree. [Press "Next" to practice using the TRAVEL key 3x]"

"Different trees give you different number of apples at the start. Exactly how many apples a tree starts with changes from tree to tree. The starting number of apples for a tree is NOT RELATED to how the tree looks or which orchard you are in. HARVESTING takes some time but earns you apples. TRAVELING takes longer, and you cannot harvest apples during traveling. But it brings you to a new tree with a full supply. You have to decide how to spend your limited time in an orchard – harvesting or traveling. You have to HARVEST each new tree once before traveling away from it. If you take too long to make a choice you will miss a turn and see this message. The more turns you miss, the less time you have to harvest apples, and you will earn less apples. That is most of what you have to know to be a great farmer. Let's go through a short practice orchard in the Apples Game."

Then participants completed a 1.5-minute orchard with no travel task. Then the learned one of the effortful travel tasks (order of effort types counterbalanced).

A. Rapid keypressing task training instructions. To train the button-pressing task participants were taught the button-press hold keys and then we challenged them to press as fast as they could across three calibration blocks. "You will now play the Button Pressing Game. Please read the instructions carefully. To play the Button Pressing Game, hold down the hold keys while rapidly pressing the press key. For your left hand, put your pinky on the A key, ring finger on the S key, middle finger on the D key, and pointer finger on the V key. For your right hand, put your pointer finger on the N key and your ring finger on the L key. First, let's try getting as many button presses as we can."

You will practice by playing 3 sets of button presses.

Great job completing those button presses! Now you will complete more presses.

Calibration block 1: "We want to know how fast you can press a button compared to other people. The computer will count up the number of presses you can complete for a short block. With your left pinky finger press the 'A' key as many times as you can before the block ends. You can stop pressing when the display changes to 'Complete!' "When you are ready to begin, start pressing the 'A' key fast as you can!"

Calibration block 2: "Great job! Take a break. When you are ready you will complete another short block. Try and complete even more presses this block! With your left pinky finger press the 'A' key as many times as you can before the block ends. You can stop pressing when the display changes to 'Complete!' When you are ready to begin, start pressing the 'A' key fast as you can!"

Calibration block 3: "Great job! Take a break. When you are ready you will complete ONE FINAL short block. Think you can complete any more presses? With your left pinky finger press the 'A' key as many times as you can before the block ends. You can stop pressing when the display changes to 'Complete!' When you are ready to begin, start pressing the 'A' key fast as you can!"

After this we computed the maximum number of presses they completed in the calibration round and set their larger (100% max) and smaller (50% max) button presses requirement.

"In this experiment sometimes you will complete a LARGE number of presses, and other times you will complete a SMALL number. You will now practice completing the [SMALL/LARGE] number of button presses. Press the 'A' key until you reach the goal number of times shown on the screen. If you do not finish in time, you will see a black circle at the end of the block. Don't worry about finishing in time; just focus on learning the timing. When you are ready to begin, start pressing the 'A' key."

"You will now practice completing the [SMALL/LARGE] number of button presses. Press the 'A' key until you reach the goal number of times shown on the screen. If you do not finish in time, you will see a black circle at the end of the block. Don't worry about finishing in time; just focus on learning the timing. When you are ready to begin, start pressing the 'A' key."

Then participants completed mini-blocks. The purpose of these blocks was to establish the expectation of completing the task during the travel time. "You will complete the [SMALL/LARGE] number of presses for [N] miniblocks. Press the F key the number of times shown on the screen. To move on to the next miniblock, you must reach the goal number of presses displayed on the screen before the deadline. If you do not finish in time, you will see a black circle at the end of the block. When you are ready to begin, press the spacebar THEN press the hold keys."

If participants failed they had to repeat the mini-block:

"Block [X] of [N]. You must repeat this block. Complete the [SMALL/LARGE] number of presses. When you are ready to begin, press the spacebar THEN press the hold keys."

If they succeeded they moved onto the next mini-block:

"Block [X] of [N]. Moving to next block. Complete the [SMALL/LARGE] number of presses. When you are ready to begin, press the spacebar THEN press the hold keys."

B. Physical Effort Foraging Task Instructions. "Here are some things to keep in mind: Sometimes you will complete a small number of presses and the background will be blue. Other times, you will complete a large number of presses and the background will be orange. If you complete the presses before the period is up, you will see "Complete!" on your screen. If you press fewer than the number of required presses, you will see a black circle. Please try to avoid seeing this circle. Now let's practice some more button presses! From now, you will play the Apples Button Pressing Game to TRAVEL from tree to tree. In some orchards you will complete the small presses when you travel and during those orchards the background will always be blue. In other orchards you will complete the large presses trials when you travel and during those orchards the background will always be orange. If you complete the presses before the travel period is up, you will see "Complete!" on your screen. Please try your best on each trial. If you make 2 errors in a row, including missing trials, you will see a black dot:

There will be a message at the start of each orchard telling you which traveling game you will play. During an orchard if you forget which task you should perform, you can look to the background color when traveling to remember. That is most of what you have to know to be a great farmer. Let's go through a short practice of the Apples Button Pressing Game."

Then participants completed a 1.5 minute orchard in the low effort (smaller number of presses) and a 1.5 minute orchard in the high effort (larger number of presses) condition.

Participants were also instructed to take a break after completing half the orchards: "You are finished with the first half, take a break and proceed to the next orchard when you are ready. [Press Spacebar to continue]"

C. Cognitive Effort Foraging instructions. "Great job harvesting in your orchard! From now, you will play the Apples Letter Matching Game to TRAVEL from tree to tree. In some orchards you will complete the 1-Back trials when you travel and during those orchards the background will always be blue. In other orchards you will complete the 3-Back trials when you travel and during those orchards the background will always be orange. Please try your best on each trial. If you make 2 errors in a row, including missing trials, you will see a black dot: There will be a message at the start of each orchard telling you which traveling game you will play. During an orchard if you forget which task you should perform you can look to the background color when traveling to remember. That is most of what you have to know to be a great farmer. Let's go through a short practice of the Apples Letter Matching Game."

Then participants completed a 1.5-minute orchard in the low effort (1-Back / congruent trials) and a 1.5-minute orchard in the high effort (3-Back / interference trials) condition.

"Great job harvesting apples! Here are a few more things you should keep in mind: You will visit 4 orchards and spend 7 minutes in each. You will know you are being moved to a new orchard when the background color changes, and you see a message like this: 'You are entering a 1-Back orchard! To earn as many apples as possible, please pay attention to how many apples a tree produces, how its supply of apples decreases, and how long it takes to travel to a new tree! Please press the spacebar to continue to the orchard.' This is everything you need to know to be a great farmer. You can make up to $5 across these 4 orchards. Remember, every apple you harvest earns you money!"

"Before you begin, you will need to pass a quiz on the instructions. Answering a question wrong will require you to re-read the instructions. Press NEXT to begin the quiz."

D. Foraging comprehension quiz. Before starting the first foraging orchard, participants were given a short quiz on the harvest and travel keys, travel task, and timing per orchard (correct answer in bold).

Quiz preamble: "Please answer every question. Answering incorrectly will require you return to the beginning of the instructions."

Quiz question 1: "What determines how long you will spend in each orchard?".

Options:

'The number of times you harvest.'

'The number of times you travel.'

'The time is fixed (1 minute).'

'The time is fixed (7 minutes).'

Quiz question 2: "When you are at a tree, how do you collect apples?".

Options:

'Repeatedly pressing the TRAVEL key (right arrow key).'

'Repeatedly pressing the HARVEST key (the down arrow key).'

'Pressing the TRAVEL key (right arrow key), once per harvest.'

'Pressing the HARVEST key (the down arrow key), once per harvest.'

Quiz question 3: "What happens to the number of apples a tree provides over time?".

Options:

'The number of apples the tree gives you decreases with each harvest.'

'The number of apples the tree gives you increases with each harvest.'

'The number of apples the tree gives you does not change with each harvest.'

Quiz question 4: "When you are at a tree, how do you leave the tree?".

Options:

'Repeatedly pressing the TRAVEL key (right arrow key).'

'Repeatedly pressing the HARVEST key (the down arrow key).'

'Pressing the TRAVEL key (right arrow key), once.'

'Pressing the HARVEST key (the down arrow key), once.'

Quiz question 5 (this question depends on the travel task): "What factor makes orchards differ from one another?".

If the travel task was N-Back:

'How any apples a tree gives on the first harvest.'

'The rate at which the number of apples at a tree falls.'

'In some orchards you will play 1-Back trials of the Letter Matching Game. In other orchards you will play 3-Back trials of the game.'

If the travel task was the Multi-source Interference Task:

'How any apples a tree gives on the first harvest.'

'The rate at which the number of apples at a tree falls.'

'In some orchards you will play matching trials of the Oddball Number Game. In other orchards you will play mismatching trials of the game.'

If the travel task was rapid keypressing:

'How any apples a tree gives on the first harvest.'

'The rate at which the number of apples at a tree falls.'

'In some orchards you will play small presses trials of the Button Pressing Game. In other orchards you will play large presses trials of the game.'

Quiz question 6: "What determines your bonus?".

Options:

'Total number of apples collected over the entire experiment.'

'Total number of apples collected on a randomly selected orchard.'

'Highest single apples value received on a randomly selected orchard.'

E. Task debrief survey. Free response questions from Experiment 2 (N-Back) including subjective awareness of travel effort cost manipulation:

How did you decide when to leave a tree?

Did the number of letters back in the traveling task change your decision to travel to a new tree? If yes, how so?

Did the number of button presses in the traveling task change your decision to travel to a new tree? If yes, how so?

Did the duration of the travel change your decision to travel to a new tree? If yes, how so?

What strategies did you use when you were harvesting a tree?

What strategies did you use in the letter matching task?

What strategies did you use in the button pressing task?

Travel task effort ratings (question order shuffled) [1 - Not effortful at all, 2, 3, 4, 5 - Very effortful]:

How effortful did you find responding 3 letters back?

How effortful did you find responding 1 letter back?

How effortful did you find completing the LARGE number of presses?

How effortful did you find completing the SMALL number of presses?

Travel task enjoyment ratings (question order shuffled) [1 - Not enjoyable at all, 2, 3, 4, 5 - Very enjoyable]:

How enjoyable did you find responding 1 letter back?

How enjoyable did you find completing the SMALL number of presses?

How enjoyable did you find responding 3 letters back?

How enjoyable did you find completing the LARGE number of presses?

Boredom ratings (question order shuffled) [1 - Not bored at all, 2, 3, 4, 5 - Extremely bored]:

How bored were you during orchards for which the traveling task was to respond 3 letters back?

How bored were you during orchards for which the traveling task was to respond 1 letter back?

How bored were you during orchards for which the traveling task was to complete the LARGE number of presses?

How bored were you during orchards for which the traveling task was to complete the SMALL number of presses?

Did you always use your non-dominant pinky finger when completing the button pressing task? [yes or no]

Subjective time perception of travel [slider 0 to 60 seconds, increments of 1 second]:

How long do you think the travel time was during orchards for which the traveling task was to respond 3 letters back?

How long do you think the travel time was during orchards for which the traveling task was to respond 1 letter back?

How long do you think the travel time was during orchards for which the traveling task was to complete the LARGE number of presses?

How long do you think the travel time was during orchards for which the traveling task was to complete the SMALL number of presses?

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