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Predicting Explore-Exploit Behavior from Personality Traits

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Abstract

The explore/exploit trade-off theorizes that individuals learn and make decisions in two different ways. Exploration entails trying new approaches that one is unsure about in order to gain new information. Exploration can be further divided into two subsections: random and directed exploration—choosing randomly when the total uncertainty is high, and choosing the most uncertain option, respectively. Exploitation involves utilizing what one already knows in order to achieve an expected result. Recent research (i.e., Gershman 2018) has demonstrated that different individuals might employ either exploration or exploitation in novel environments, but whether different personality traits influence the strategy that is used is a relatively unexplored area of inquiry. In the present study, we asked 67 participants to complete a choice-based, point-scoring computer task. We instructed participants to collect as many points (in the form of numerical value feedback) as they could by selecting among four options, some of which offered a steady stream of points, and others which were more randomized. Participants also completed an abridged form of the Big Five personality questionnaire. We hypothesized that negative emotionality would correlate negatively with directed exploration, that open-mindedness would correlate positively with both measures of exploration, and that impulsivity would correlate positively with random exploration. We did not find support for any of the three hypotheses; rather, the opposite occurred in negative emotionality and directed exploration ($p = 0.018$, $r = 0.29$). These findings can be applied in various fields of research, as they demonstrate variation in types of learning and decision-making styles across different settings.

1. Introduction

Everyone, at one point or another, has faced a decision as to whether they will continue with what is familiar or look for something new. Such a decision could pertain to many different aspects of life, from something as simple as what to eat for lunch all the way to something as monumental as a potential career change. The explore/exploit trade-off dictates that, in making a given decision, there are two paths that an individual can take. The first path involves choosing a route that one is unsure about in order to gain new information (exploration). The second path involves choosing to continue with what one is already familiar with in order to achieve a known result (exploitation). Prior research (i.e., Wilson et al., 2014) has shown that different people may employ either of the two paths in different situations, but whether individual personality traits influence the path that an individual is more likely to choose is a relatively unexplored domain.

The trade-off between exploration and exploitation has been observed in many different species at evolutionary scales. The ability to decide to either explore or exploit has evolved to help animals, including humans, survive in the natural world (Addicott et al., 2017). It has been postulated that this decision-making process may be correlated with various neurobiological processes

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(Addicott et al., 2017). Beeler et al. (2012) theorized that midbrain dopamine plays a significant role in the regulation of explore/exploit learning and decision-making. This research suggests that increased dopamine function promotes exploration, whereas decreased dopamine function promotes exploitation. This phenomenon is linked to energy conservation; dopamine function promotes an increase in energy expenditure, thus leading to more exploration, and vice versa. Furthermore, there is evidence that dopamine receptors in the prefrontal cortex help to monitor changes in reward probabilities, which may have an effect on one's likelihood to either explore or exploit (Addicott et al., 2017).

In order to delve further into exploration/exploitation research, it must be noted that exploration can be divided into two subcategories: random and directed exploration. In random exploration, exploratory options are chosen randomly when the total uncertainty is high; in directed exploration, choices that are made are biased towards the option that may provide the most new information, typically the most uncertain option (Gershman, 2018; Wilson et al., 2014). Historically, there have been contradictory results regarding directed exploration, as it is difficult to observe/confirm its existence in the presence of a reward. However, more recently, some psychiatric research has examined how directed exploration may manifest in various mental and substance abuse disorders.

To understand how exploration/exploitation is measured in a laboratory setting, it is critical to explain the three behavioral paradigms that are used most often: the *n*-armed bandit task, the 2-armed leapfrog task, and the clock task. The *n*-armed bandit task refers to a behavioral task in which participants see *n* amount of options (typically presented as simulated slot machines) that they can choose from. After a participant selects an option, they are shown a reward value. The values of each option are predetermined via an algorithm, and the value of each option changes with each trial, independently of each other. This task measures explore/exploit behavior based on the option that the participant tends to choose: if they choose the option that previously yielded many points, for instance, and they continue to choose it even after the point value goes down, then they are exploiting.

The 2-armed leapfrog task is similar in appearance to the *n*-armed bandit task, but with two options rather than *n*. In this task, each option is assigned a different reward value, but one option always has a higher reward than the other. There is a fixed probability that the option that yielded the smaller reward in the previous trial will increase in value, becoming the better option (Addicott et al., 2017). This task measures explore/exploit behavior in a similar way to the *n*-armed bandit task; however, participants are more limited in their choices.

The clock face task is another behavioral task, in which participants are shown a clock face with a hand that rotates clockwise in 5-second increments. Participants are instructed to stop the hand to obtain a reward, which is revealed to them after the choice is made. This task measures exploitation by giving participants fixed reward values that occur across all trials and analyzing their behavior when they learn where the highest reward values are. This particular task is limited in that it is difficult to observe a concrete distinction between exploration and what is known as "decision noise," or human variability (Addicott et al., 2017).

Some prior research has endeavored to understand mental health as an explanatory variable for explore/exploit behaviors. A study conducted by Blanco et al. (2013), for instance, examined the extent to which symptoms of depression influenced exploratory decision making. It has been suggested that individuals diagnosed with depression should exhibit difficulties with maintaining an accurate mental representation of the novel environment due to characteristic deficits in planning and working memory (Blanco et al., 2013). Thus, depressive individuals may be more likely to explore the environment in comparison to non-depressive individuals. In Blanco et al.'s study, the 2-armed leapfrog task was used to measure exploration/exploitation learning and behavior. The researchers found that depressive participants explored more often and that the higher reward option was chosen slightly less often than in non-depressive participants. The study concluded that the exploration that individuals with depressive symptoms exhibited was undirected (random) exploration. However, this study is limited in its inability to determine whether accompanying anxiety levels contributed to any of the results that were observed (Blanco et al., 2013).

To demonstrate the effects of anxiety on exploration/exploitation learning and behavior, Fan et al. (2022) recruited participants with and without trait somatic anxiety—anxiety with the tendency to experience physical symptoms. In their study, Fan et al. (2022) conducted two different experiments. Both experiments featured a 2-armed bandit task, but the second variation included a reward prediction task at the end of each task block. In participants without trait somatic anxiety, the researchers found that directed exploration was used most often, with the most uncertain option being the one that the most participants formed a bias towards. However, the researchers also found evidence for random exploration, suggesting that participants tended to choose more randomly when the overall uncertainty was high, rather than when one option in particular was more uncertain than others (Fan et al., 2022). In participants with trait somatic anxiety, the researchers found that there was a reduction in both directed and random exploration, with a tendency to choose the option with a higher expected value more often than any of the other values (Fan et al., 2022). This study is limited, however, in that Fan et al. did not examine other psychiatric symptoms that may have a high comorbidity with anxiety, such as depression.

Similarly, Smith et al. (2022) examined the effects that both anxiety and depression had on exploration/exploitation learning and behavior—more specifically, on directed exploration. In this study, participants with symptoms of both anxiety and depression completed a task similar to the 2-armed leapfrog task. The researchers found that participants with more severe symptoms used directed exploration less than those with milder symptoms, and that severe depression and anxiety symptoms were associated with a higher desire to reduce overall uncertainty. Smith et al. also examined cognitive reflection, or the ability to reflect on a question and "override" an initial "gut feeling." They found that individuals with more severe symptoms exhibited less reflectiveness and that this decrease in reflectiveness led to greater random exploration. Contrary to the findings from Fan et al. (2022), this research suggests a relative increase in random exploration occurs amongst more severely affected individuals.

In another area of mental disorder research, Addicott et al. (2021) studied the effects of attention-deficit/hyperactivity disorder (ADHD) on exploration/exploitation learning and behavior. ADHD is associated with lower dopamine levels due to increased reuptake, reducing one's sensitivity to reward. In this study, participants who were clinically diagnosed with ADHD, as well as participants who did not have ADHD, completed a 6-armed bandit task. Some participants were given Methylphenidate (MPH), a psychostimulant that is regularly prescribed for those with ADHD as it blocks dopamine reuptake; others were not. In both treatment groups (administered and not administered MPH), individuals with ADHD explored more (and more randomly) than those without ADHD. These findings contradict Beeler et al.'s (2012) results, highlighting the need for more research in this area to address the currently unresolved discrepancies in the literature.

While the above studies discuss the impact of various mental disorders on exploration/exploitation learning and behavior, Park and Kim (2021) shift gears and focus on the impact of specific personality traits on decision-making. Park and Kim's study also differs in that it was conducted in a workplace setting using questionnaires that were adapted to the participants' environment, rather than providing them with a specific, unrelated task.Participants were asked questions about two of the Big Five personality traits—open-mindedness and conscientiousness—and about their own perceived levels of exploration and exploitation behaviors. Park and Kim found that participants with a higher level of open-mindedness tended to use exploration more in their daily activities, as opposed to those with a lower level of open-mindedness. Meanwhile, participants with a higher level of conscientiousness employed more exploitation in their daily activities. One limitation of this study, however, is its complete reliance on self-reported data, which may have resulted in some inaccuracies.

In dialogue with the existing literature, the present study aims to analyze the impact of three different personality traits on exploration/exploitation learning and behavior. Specifically, this study intends to observe whether these personality traits have an impact on exploration behavior. Negative emotionality—neuroticism, a vulnerability factor in the development of anxiety (He et al., 2021)—open-mindedness, and impulsivity—a potential symptom of both anxiety and ADHD (Bakhshani, 2014)—are measured alongside exploration/exploitation learning and behavior. Negative emotionality and open-mindedness are measured using the Big Five personality questionnaire, and impulsivity is measured using the Barratt scale. Exploration/exploitation behavior is observed using a 4-armed bandit task.

We hypothesize that negative emotionality correlates negatively with directed exploration due to the decrease in directed exploration in participants with anxiety in the experiments of both Fan et al. (2022) and Smith et al. (2022). We also hypothesize that open-mindedness correlates positively with all exploration, as shown in Park & Kim (2021). Our final hypothesis is that impulsivity correlates positively with random exploration, due in part to the notion that impulsivity is a symptom of ADHD, and that individuals with ADHD tend to use random exploration more often (Addicott et al., 2021).

2. Methods

2.1. Participants

Participants (n = 67) aged 18–23 were recruited from the University of Oregon undergraduate community via the University's SONA research system. Course credit was offered in exchange for participation.

All participants provided written informed consent, and experimental procedures were approved by Research Compliance Services at the University of Oregon.

2.2. Experimental Design

Participants completed a 4-armed bandit task in which they were shown four simulated "slot machines" of different colors and were told that their objective was to gain as many points as possible. In each trial, participants were given 1.5 seconds to select a slot machine, followed by a 1.5-second animation of the slot machine "rotating"; then, the point value associated with the option they selected was displayed for another 1.5 seconds.

Following the display of the point value, participants were shown a fixation cross (signifying the end of the trial), and then they were presented with the array of slot machines again. This process, seen in Figure 1, was repeated for a total of 201 trials. Following the completion of the 4-armed bandit task, participants were asked to complete the Barratt Impulsiveness Scale (Barratt) and the Big Five Inventory 2-Short Form (BFI-2-S).

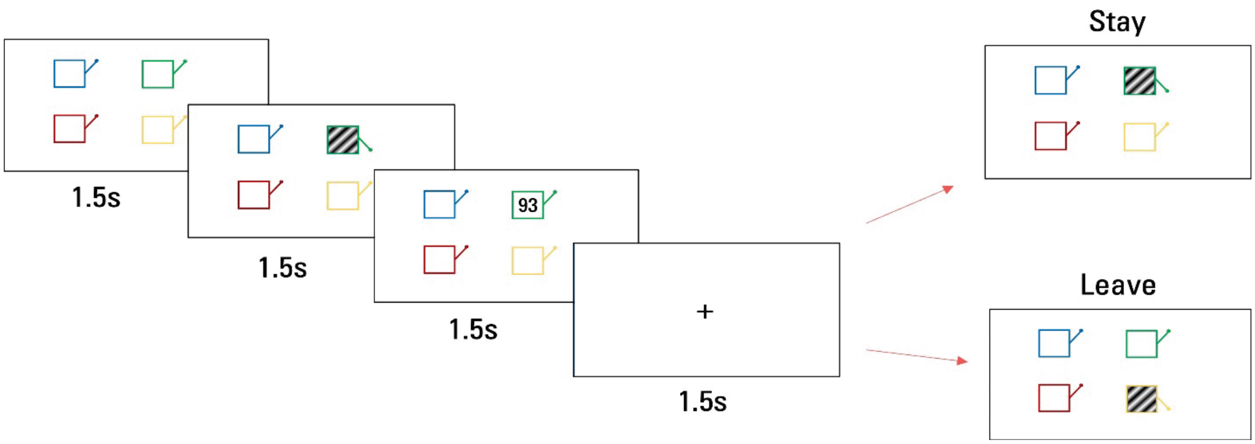

Figure 1. Task design. The "slot machines" that participants viewed were of four different colors: blue, green, red, and yellow. Following the selection of a slot machine, participants were shown the points received and then a black fixation cross. Following the fixation cross, participants continued on to the next trial, choosing whether they wanted to pick the same option again (stay) or move to a different option (leave).

In order to determine the point values that would be displayed to participants, values between 0 and 100 were randomly sampled from a normal distribution for every trial. A normal distribution is characterized by its first two moments: its mean (i.e., peak) and variance (i.e., width). Following the protocol of Daw et al. (2006), upon which the current task is based, variance was fixed at 2, while mean was determined by a Gaussian random walk. On the first trial, we sampled a normal distribution with a mean of 50. On every subsequent trial, we sampled a normal distribution with a mean equal to the previous trial's outcome plus a small value (also sampled from a normal distribution but with a variance of 2.8 and mean of 0), known as an error parameter. We applied the Gaussian random walk to all four of the options separately.

A Gaussian random walk ensures that an option's value on the current trial is similar to the same option's value on the previous trial, but not exactly the same. The similarity from trial to trial means that an option's value slowly drifts, enabling participants to pick up on trends across trials. Additionally, the error parameter ensures that the option with the highest payout changes across the duration of the task. The point values are defined by this specific function because it enables the learning of trends and the observation of whether participants change their choices after trends reverse. This design allows us to visualize explore-exploit behavior, because participants that exploit will continue to choose the initial "good" option even after the trend reverses. We can also analyze how often participants explore by counting the number of times they choose options that are not necessarily the "best" choice. This analysis was used by Daw et al. (2006) to define exploration and exploitation, but here, we are specifically seeking to dissociate exploration between random and directed subtypes.

2.3. Data Analysis

Rather than using the objective feedback (actual point values) that participants saw on each trial, we created a computational model that estimates the subjective value of every option on every trial, regardless of whether a participant picked it or not. We used a probabilistic reinforcement learning model that makes normally distributed predictions for the value of every option on every trial in order to analyze the subtypes of exploration. Using this probabilistic reinforcement learning model, we defined subjective value as the mean of the distributions and uncertainty as the variance. Exploitation is rechoosing the option with the highest previous mean (or subjective value), directed exploration involves choosing the option with the highest variance (or uncertainty), and random exploration is choosing one of the other two options.

We used this labelling system to classify every decision that participants made as either exploitation, directed exploration, or random exploration. We report the proportion of all trials that participants used either strategy, as well as the standard deviation of these averages, as seen in Figure 2.

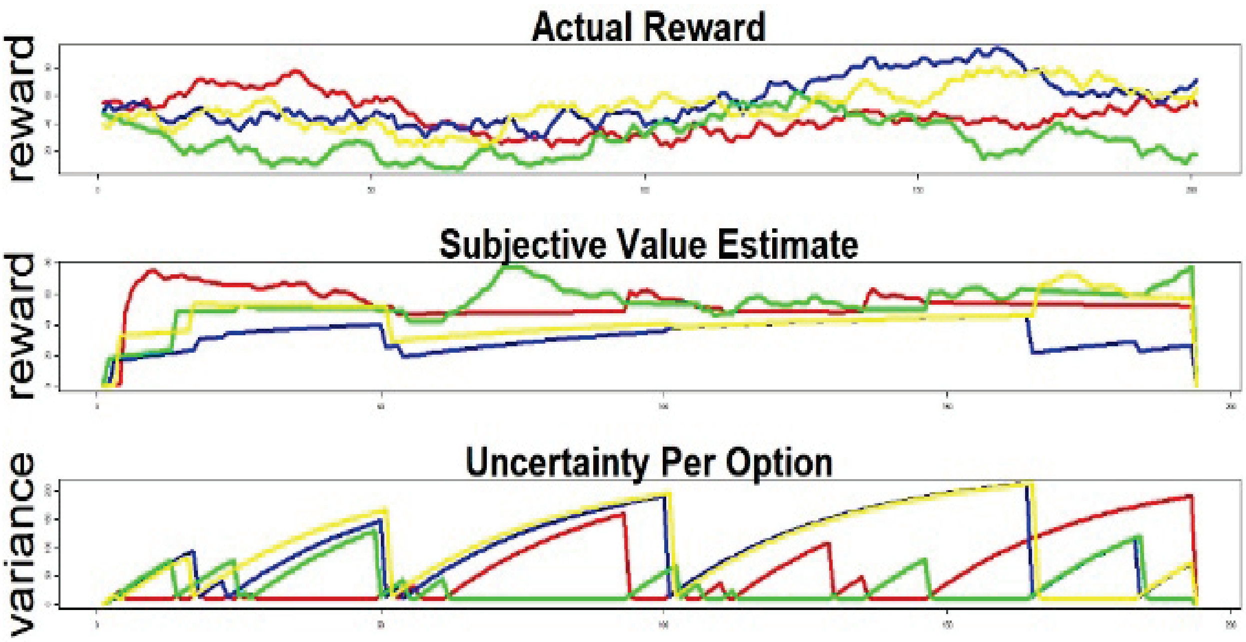

Figure 2. Reward values and uncertainty for one participant. The "actual reward" graph visualizes the point values for each slot machine (color coded by slot machine). The "subjective value" estimate visualizes the model's estimation of point values based off one subject's second trial rather than the first, as we cannot estimate the subjective value for the current trial without having the actual reward from the previous trial to base it on.. "Uncertainty per option" is the perceived variance of each option.

To obtain measures of negative emotionality and open-mindedness, we used the scoring system of the Big Five short form (BFI-2-S; Soto & John, 2017), and to obtain the measure of impulsivity, we used the revised Barratt Impulsiveness Scale (Patton et al., 1995). Higher scores in the categories of negative emotionality, open-mindedness, and impulsivity indicate higher negative emotionality, open-mindedness, and impulsivity, respectively.

To test our predictions of relationships between reinforcement learning strategies and personality, we conducted three Pearson's correlation tests, for which we report t-statistics, 95% confidence intervals, correlation coefficients (r), and p-values. We reject the null hypothesis—no relationship between the correlated measures—if the p-value is less than our alpha threshold, which we set at 0.05.

4. Results

4.1. Modeling results

To validate the distinction between the three methods of exploration/exploitation, we examined the average proportions in which each method was used by participants across all trials. We found that exploitation was used most frequently ($\mu = 0.630$, $SD = 0.242$), and directed exploration was the second-most-frequently used method ($\mu = 0.199$, $SD = 0.142$). Random exploration was used the least often across all of the different trials ($\mu = 0.170$, $SD = 0.132$). These results are reported in Figure 3.

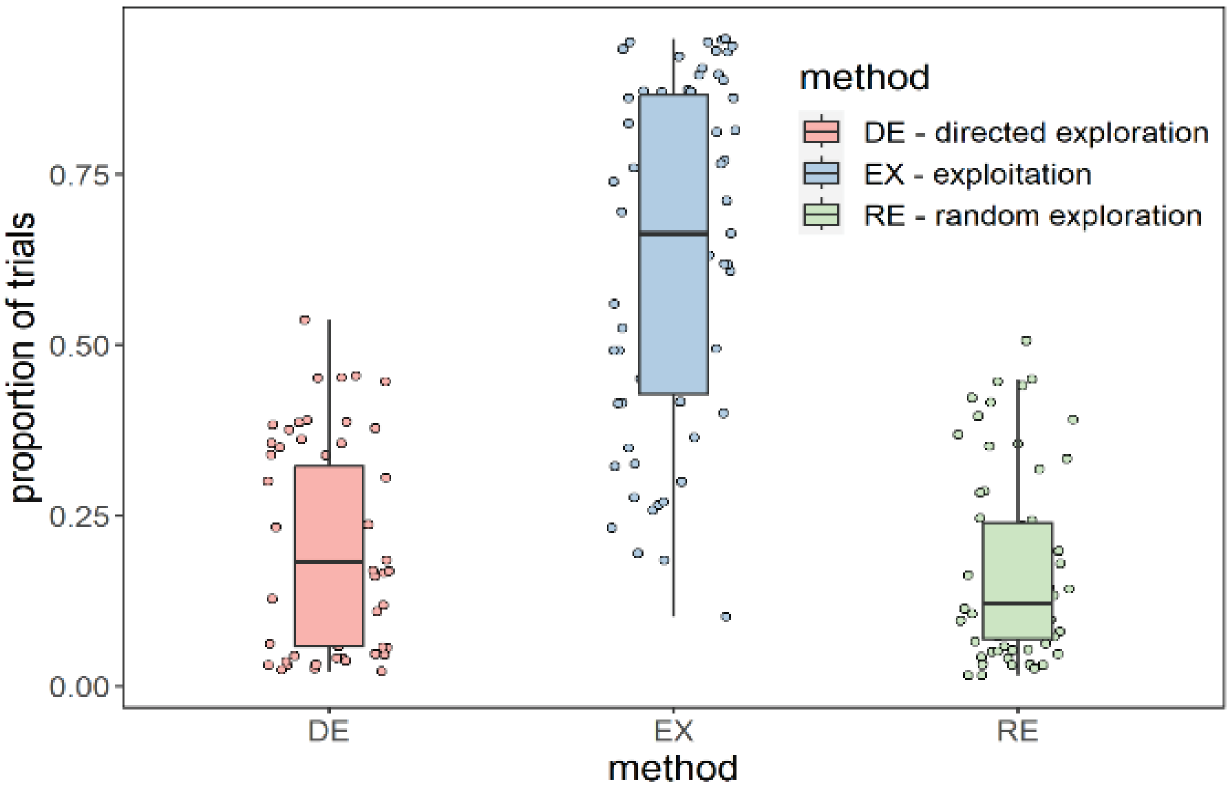

Figure 3. Proportion of usage of explore/exploit methods. Points represent the mean proportion of trials in which each method was used across all participants.

4.2. Correlations

Figure 4 visualizes all correlations across the three methods of exploration/exploitation.

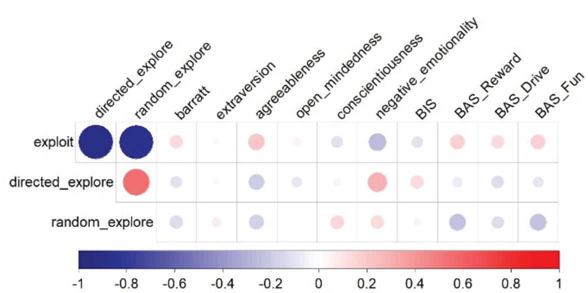

Figure 4. Correlation matrix showing Pearson's r across the three methods and every measured variable. A negative r coefficient is displayed in a blue hue, and a positive r coefficient is displayed in a red hue. A stronger correlation coefficient is shown as a larger circle in a darker shade.

There is a moderately strong correlation between negative emotionality and directed exploration, meaning that higher levels of negative emotionality significantly predicted an increased rate of directed exploration ($t(67) = 2.43$, $p = 0.018$, 95% CI = [0.05, 0.494], $r = 0.29$) (Figure 5).

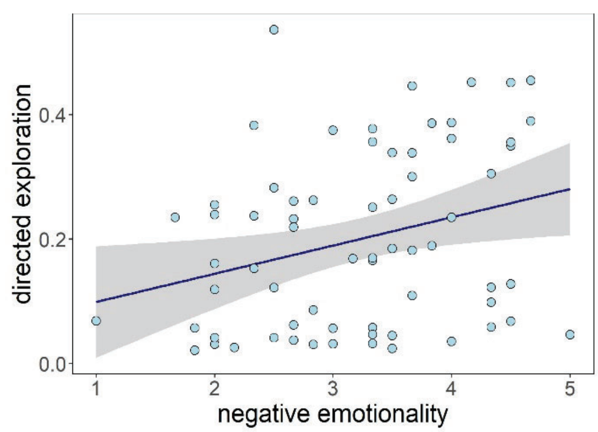

Figure 5. Correlation between directed exploration and negative emotionality (r = 0.29). Points represent individual participants.

Random exploration trended negatively with increased impulsivity; however, the relationship is not significant ($t(67) = -1.12$, $p = 0.266$, 95% CI = [-0.366, 0.106], $r = -0.14$) (Figure 6).

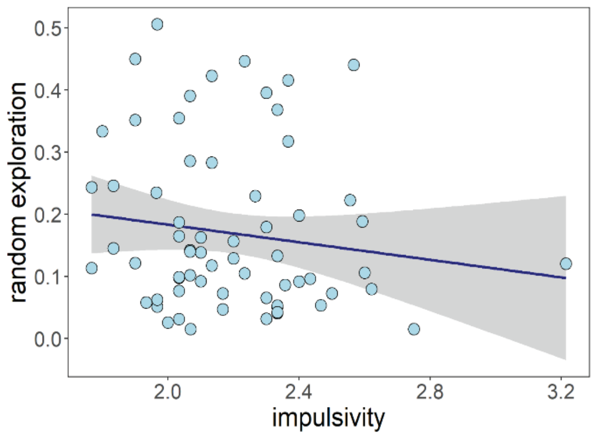

Figure 6. Correlation between random exploration and impulsivity (r = -0.14). Points represent individual participants.

Open-mindedness had virtually no effect on either directed (t(67) = -0.647, p = 0.520, 95% CI [-0.314, 0.163], r = -0.080) or random exploration (t(67) = -0.095, p = 0.924, 95% CI = [-0.251, 0.229], r = -0.012) (Figure 7).

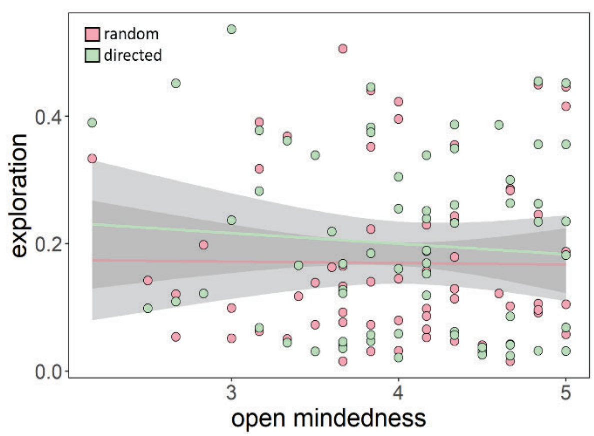

Figure 7. Correlation between subtypes of exploration and open-mindedness (directed—r = -0.080; random—r = -0.012). Points represent individual participants.

5. Discussion

Balancing exploration and exploitation is an adaptive decision-making strategy that has evolved to help animals, including humans, survive in the natural world (Addicott et al., 2017). Optimizing this trade-off has proved helpful in improving overall decision-making performance, increasing learning rate, and enhancing decision-making skills. Previous research (Gershman, 2018; Wilson et al., 2014) has found that exploration can be further divided into directed and random exploration, and recent research (Fan et al., 2022; Smith et al., 2022) has attempted to depict a correlational relationship between these subtypes and various psychiatric disorders. The present study aimed to identify a relationship between personality traits that may be vulnerability factors for developing different psychiatric disorders and subtypes of exploration.

Contrary to our hypothesis, we found a significant, direct relationship between negative emotionality and directed exploration—higher levels of negative emotionality significantly predicted an increased rate of directed exploration (Figure 5). Previous research has found the opposite relationship between anxiety (both trait somatic and general) and directed exploration (Fan et al., 2022; Smith et al., 2022). Our empirically informed hypothesis, that we would observe a decreased rate of directed exploration in those with higher levels of negative emotionality, has not been supported by our findings. This discrepancy may be explained by the "intolerance of uncertainty" among more neurotic individuals or individuals with anxiety (Gu et al., 2020). We theorize that participants who score higher on the negative emotionality scale may engage in directed exploration more often so as to target the most uncertain options and "get them out of the way." Further research should be conducted in order to examine this relationship.

We also found that there was not a significant relationship between impulsivity and random exploration (Figure 6). Rather, our results depict a negative trend in this relationship—increased impulsivity may result in decreased random exploration. Previous research has found the opposite relationship, wherein higher levels of impulsivity did indicate a higher rate of random exploration (Dubois & Hauser, 2022). Some studies have also found an increased rate of random exploration in participants with ADHD (Addicott et al., 2021). Seeing as impulsivity is a symptom of ADHD, we expected to see similar results in the present study. However, one dimension of impulsivity is a lack of premeditation, meaning that more impulsive individuals may react or choose without thinking (Miller et al., 2003). If an individual were to simply pick an option truly randomly (without thinking), they may happen to actually choose to exploit rather than selecting one of the options that they are uncertain about specifically. Still, we do not currently have any evidence to substantiate this theory other than an extremely slight positive correlation (see Figure 4), so further research should be conducted in order to examine this potential relationship.

We found no significant relationship between open-mindedness and the subtypes of exploration (Figure 7). Previous research has shown that increased open-mindedness is correlated positively with an increased rate of overall exploration (Park & Kim, 2022). However, the distinction between directed and random exploration has not been made. We theorize that we would need a larger sample size in order to make any further conclusions about open-mindedness and exploration.

The present study has a few noteworthy limitations, the most obvious of which is its small sample size. Although a sample of 67 participants is adequate for preliminary research, it is not sufficient to draw strong conclusions or to detect more subtle effects. More participant data collection is necessary in order to observe whether these preliminary results will change or strengthen. Another limitation to this study is that we did not screen participants for neurotypicality. Some participants may already have and/or exhibit symptoms of anxiety, depression, or ADHD, which may have exaggerated or understated our results. Lastly, our sample size was confined to college-going individuals 18–23 years of age. We do not know if these results would replicate in older or younger populations.

To further expand upon this research, a few different routes can be taken. First, this study could benefit from a larger sample size across a broader age range in order to observe whether there are any age-related differences in the effect of personality traits on explore-exploit behavior. Another way to conduct more research on this subject would be to administer different personality questionnaires—such as the Rosenberg Self-Esteem Scale or the Aggression Questionnaire—in order to see if other traits may have a stronger correlation with exploration subtypes and/or exploitation. Studying these other traits across different age groups may provide even more insight as to which individuals make certain types of decisions. Finally, to expand upon this line of research even further—more specifically, upon the findings from Beeler et al. (2012) and Addicott et al. (2021)—we can adapt the 4-armed bandit task for use in a functional magnetic resonance imaging (fMRI) setting. This would offer more insight into the neurological bases of the different decision-making strategies and how differences in personality type may appear in the brain (i.e., *If someone were higher on the negative emotionality scale and used more directed exploration, would that look differently in their brain than in someone who was lower on the same scale and also used more directed exploration?*). All of these possible routes for pursuing further research would increase scientific understanding of the explore-exploit trade-off and how it varies across demographics and personality types.

Despite the limitations of this study, our results indicate that there may indeed be a correlational relationship between personality traits and explore-exploit behavior. This finding may be helpful in understanding why certain individuals make the decisions that they make. A choice process that makes sense for someone who is higher on the negative emotionality scale might not occur in an individual who is lower. Furthermore, deeper investigation can identify stronger correlational relationships, which can then lead to a stronger prediction of behaviors (i.e., if someone scores very highly on the negative emotionality scale, then we anticipate that they will exclusively use directed exploration). This study may have implications for various areas of research, such as business/economics (learning what decisions different people may make in certain financial situations) and psychiatry (making inferences as to how individuals with different disorders may base their decisions). In a day-to-day setting, this research can also aid in a greater understanding of those around us and the decisions they make.

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