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ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Original Article

A bias toward the unknown: individual and environmental factors influencing exploratory behavior

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With limited resources, exploring new opportunities is crucial for survival. Exploring novel options, however, comes at the cost of uncertainty. Therefore, there is a trade-off between exploiting options with a known beneficial outcome and exploring novel options with a potentially higher gain. Computational models have suggested that novelty may promote exploratory behavior by inducing a so-called *novelty bonus* through reward-related processes. So far, few studies have provided behavioral evidence for such a novelty bonus. In this study, we aimed to investigate whether *spatial novelty* can stimulate exploratory behavior (Experiment 1), and whether age, novelty-seeking, and reduced action radius or social interactions due to COVID-19 restrictions influenced the exploration–exploitation trade-off (Experiment 2). In both experiments, we employed a novel paradigm in which participants made binary decisions between food items, while on rare trials, a surprise option was presented. Results from Experiment 1 are in line with a novelty bonus, with spatial novelty promoting exploratory behavior. In Experiment 2, we found that exploratory behavior declined with age, high novelty seekers made more exploratory choices than low novelty seekers, and participants with a smaller action radius made fewer exploratory choices. These findings are consistent with previous findings in animals and predictions from computational models.

Keywords: novelty; exploration; food choices; value; surprise; decision making

Introduction

The exploration–exploitation trade-off

“A bird in the hand is worth two in the bush.” This old English saying expresses a preference for certain over uncertain outcomes. Although exploitation of what is available may be beneficial in the short-term, resources will always run out over time, and exploring the environment to locate new feeding grounds is crucial for mammals to survive.[1] When visiting a new environment, however, it is unknown where danger lurks and where to find rewards, therefore, there is a constant trade-off to be made, weighing the risks of exploring novel opportunities, against the chances of resources running out when exploiting familiar ones.[2] The exploration–exploitation trade-off has already been investigated quite extensively in both humans and nonhuman animals,[3] but experimental studies investigating the effects of novelty on this trade-off are scarce. Specifically, the effects of exposure to novel environments on exploration have not yet been addressed in humans. Here, we aimed to investigate the effects of spatial novelty on exploratory behavior, and to further identify factors of influence, addressing the role of age and the novelty-seeking trait. Making use of the exceptional situation of a COVID-19–related lockdown, we further addressed the link between exploratory behavior, social interactions, and action radius.

As there are costs associated with exploring novel options, such as dealing with uncertainty and unexpected danger, it has been suggested that novelty may energize motivation to explore via dopaminergic reward pathways in the brain,[4–6] while familiar

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contexts may induce exploitative behavior.[2] Previous work has, indeed, shown that in a value-based choice task, the perceptual novelty or familiarity of the options influences choice behavior.[7] Novelty was shown to drive choices regardless of choice outcome. Computational models have suggested that novelty can promote exploration via motivational networks.[8] This effect has been described as a *novelty bonus* or *exploration bonus*.[5,9–11] Earlier work has suggested that personality traits, such as novelty seeking, can bias decisions toward either exploration or exploitation.[7,12,13] A reason for this may be that high novelty seekers value novelty more than low novelty seekers, as suggested by a neuroimaging study in which novelty seekers were motivated by novelty independently of the underlying reward function.[14] Taken together, these studies suggest that individual differences in the novelty-seeking trait may influence the exploration–exploitation trade-off via motivational pathways. But so far, no studies have addressed the role of the novelty-seeking trait in the exploration–exploitaiton trade-off in food-related choices in humans.

Factors influencing the exploration–exploitation trade-off

Another factor that may influence exploratory decision making is happiness. As both happiness and exploratory decision making are associated with striatal dopamine, potentially happiness could promote exploratory behavior.[15,16] In one study, levodopa was used to boost dopamine levels in human participants. It was found that higher levels of dopamine were associated with more risky choices when participants could gain but not lose monetary rewards, and dopamine boosted happiness after certain rewards.[17] As exploitation relies on safer well-learned contingencies, while exploration involves larger risks,[18] the riskier behavior in that study could thus be linked to dopamine-driven exploratory behavior and happiness.[17] Other studies, however, failed to find direct effects of happiness on exploratory or exploitatory behavior,[19,20] and the link between happiness and the exploration–exploitation trade-off remains unclear.

Furthermore, age may influence exploratory behavior. Older adults show lower risk-taking behavior and prefer familiar over novel options.[21] In search tasks, they exploit resources more than they explore new ones.[22] These reductions in risk-taking and exploration behavior match the rise and fall of the dopaminergic system across the life span, with a deterioration of dopaminergic functioning in old age.[23–26] Therefore, when investigating exploratory behavior, it is relevant to take age into account.

In food-related decision making, humans have a tendency toward neophobia, as evidenced by a preference for familiar over unfamiliar foods (note: here familiarity is quantified by individuals' subjective recognizability ratings of food items, or an experimental manipulation in which either real ("familiar") or fictitious ("novel") food items are labeled and described).[27,28] This preference for familiar foods can be regarded as exploitative behavior, but there are some factors in addition to novelty that can tip the balance toward exploration. In the first place, foods may be evaluated according to their affective valence.[29] But also internal states may play a role: hunger can promote exploration of environments as observed in studies with rodents and similar findings have been obtained with multiagent models.[30–32] This is also in line with the finding that people scoring higher on neophobia have lower calorie intakes as well as a poorer dietary quality than people with a more neophilic disposition.[33,34] As such, methods that can increase exploratory behavior could potentially be employed to promote more diverse and nutrient-rich eating habits, which may be especially relevant during the current COVID-19 pandemic.[35–38]

Exposure to novel environments

Previous work has shown that exposure to novel environments can promote learning,[6,39,40] with novelty promoting dopamine release in the hippocampus.[41–43] Spatial novelty, thus, has been shown to promote memory, and novel options may be favored due to so-called novelty bonuses. Work in rodents has further suggested that environmental enrichment, such as exposure to novel environments, is associated with better performance on exploratory tasks.[44] In contrast, rodents reared in conditions of deprivation (i.e., perceptually or socially impoverished environments) exhibit reduced open-field exploration.[45,46] This suggests that exploration behavior may be influenced by previous experiences or lack thereof, but work on the effects of impoverishment on exploratory behavior in humans is currently lacking.

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One way to investigate the effects of spatial novelty would be to expose people to novel and previously familiarized environments, but the effects of environmental impoverishment have not been investigated experimentally in humans due to ethical reasons. During the COVID-19 pandemic, however, many countries limited citizens' movements. For example, some countries or states restricted people to going outside during certain times (a curfew), closed shops, limited exercise options, and generally recommended people to stay inside as much as possible. Although it was previously impossible due to ethical reasons to investigate the effects of impoverishment in an experimental fashion in humans, the COVID-19 pandemic created a unique situation during which people experienced limitations to their free movement, reducing their action radius as a result. As novelty has been suggested to promote exploratory behavior,[11] it is possible that less exposure to novel stimulation due to a reduced action radius during the COVID-19 pandemic negatively affected exploratory behavior, which is what we set out to investigate in the present study.

Current study

In the current study, we performed an experiment investigating the effects of spatial novelty on exploratory behavior using a value-based food choice task (Experiment 1). In an online study (Experiment 2), we investigated other factors that could influence exploration behavior, such as age, the novelty-seeking trait, and action radius (utilizing the uniqueness of the COVID-19–related lockdown situation, which restricted movements outside the house for many). On some trials, one of the options was a surprise box for which the contents were unknown. The percentage of surprise item choices was taken as a measure of exploratory behavior. We aimed to investigate whether *spatial novelty* can promote exploratory behavior (Experiment 1) and to identify other factors influencing exploration (Experiment 2). In Experiment 1, participants performed the food choice task in either a previously familiarized or a novel environment. We expected participants to make more exploratory choices in the novel compared with the familiar environment. In Experiment 2, we expected that exploratory behavior would decrease with increasing age and reduced action radius. In contrast, hunger and happiness were expected to promote exploration behavior, and high novelty seekers were expected to make more exploratory choices than low novelty seekers.

Methods for Experiment 1 (novelty in the lab)

Participants

Eighteen participants (15 females, 3 males; age: 18–30; mean age = 22.2, SD = 3.3) volunteered for the lab experiment and received course credit as well as one food item as compensation. All participants reported having normal or corrected-to-normal vision. Exclusion criteria were a history of neurological or psychiatric disorders, and/or current intake of psychotropic medication. An age limit of 45 years was set, as the dopaminergic system, which is believed to drive exploratory decision making, declines in older age.[11] We originally intended to recruit more participants (i.e., ∼30 based on a previous power analysis based on Ref. 6), but as we started our lab study in February 2020, we had to stop our lab study after a month due to following lockdown restrictions. All participants provided written informed consent. Ethical approval was obtained from the Psychology Research Ethics Committee (CEP) of the Faculty of Social and Behavioural Sciences at Leiden University. The study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Procedure

Figure 1 shows the general design of the experiment. The experiment took place on three separate days, with at least 24 and a maximum of 48 h in between the sessions. On the first testing day, participants filled out the Behavior Inhibition/Activation Scale (BIS/BAS),[47] the Tridimensional Personality Questionnaire – novelty-seeking subscale (TPQ_NS),[12,13] and a demographics questionnaire. The BIS/BAS is an instrument to assess reward responsiveness and drive, among others, and consists of 24 items on a 4-point Likert scale. It can, therefore, be seen as a self-report measure of dopamine sensitivity. The TPQ is a personality test consisting of the three subscales: novelty seeking, harm avoidance, and reward dependence. In line with data minimization principles, we only assessed the novelty-seeking subscale as an indicator of the

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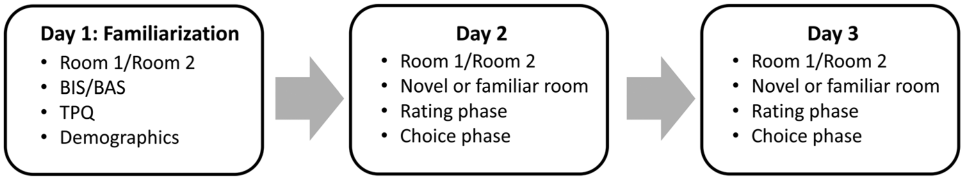

Figure 1. Experimental design. The experiment took place in two rooms. On the first day, participants filled out questionnaires and were familiarized with one of two rooms. Which room was familiarized was counterbalanced in a between-subjects design. On days 2 and 3, participants performed the experimental task in the same room as day 1 (familiar condition) and a different room (novel condition) in a within-subjects design. The order of the conditions (novel first; familiar first) was also counterbalanced between participants.

trait counterpart to the behavioral findings in the lab. This scale spans 34 items and has a yes/no answer format.

The session on day 1 was finished in about 10–15 min and took place in one of two potential labs. As such, the session on day 1 also acted as a familiarization phase for that location. On days 2 and 3, participants were tested in the same room (familiar condition) and another room (novel condition). The order (novel first or familiar first) and location (room 1 or room 2) were counterbalanced between participants. The two labs were differently decorated to ensure that participants could distinguish the different locations.

Before the experiment, the food items that participants would be able to choose from during the experiment were shown on a table, to increase their familiarity with the options and to make the choices more realistic. At the beginning of the experimental procedure, participants indicated their age, rated their hunger on a 7-point scale, and indicated how much time had passed since their last food intake. In the following experimental task, participants first rated the desirability of 40 food items during a *rating phase* (Fig. 2A). During this phase, a trial started with the presentation of a fixation dot for 500 milliseconds. The fixation was followed by the presentation of a food item, which was shown for 2000 milliseconds. After this, a slider was shown which participants could move using the mouse to indicate the desirability of the previously shown item ("How much would you like to eat this item after the experiment?") on an underlying 100-point scale. With this question, we aimed to estimate the motivational value of the food item for each individual.[48] Berridge and Robinson distinguish between two motivational concepts: one related to the hedonic response to the outcome ("liking") and the other related to the incentive salience ("wanting").[49] Although our question included the word "like," we expect that our question also reflects the *wanting* response, as the consequence of the question involves the action of eating the item, rather than the mere evaluation of it. The slider to indicate the desirability was shown until a response was given. All 40 food items were presented in a random order. In the following *choice phase* (Fig. 2B), trials again started with a 500 ms fixation dot. After fixation, one food item was shown to the left and another to the right of fixation. The combinations of food items were predetermined such that unique combinations were always shown, but the combinations for different participants were the same. The presentation of the combinations was randomized for each participant. Participants were asked to choose the most desirable item by pressing left ("x") or right ("m") using their left and right index fingers. A new trial was started when a response was given or after a time-out of 2500 milliseconds. Each pair of options was repeated six times with item location (left/right) randomized. During the choice phase, participants made a total of 240 choices. In 20% of the trials, a surprise option was presented. A picture of a black box indicated that a food item was "hidden" in it. After choosing this box, participants were shown what was "inside" for 750 milliseconds. Participants could take a self-paced break after every 80 choice trials. During each block, all 40 choice pairs were presented twice. After the experimental procedure, participants would receive one of their choice items, making their choices during the experiment more realistic. The average duration of a block was 5 min, and the entire session was completed in about 20 minutes.

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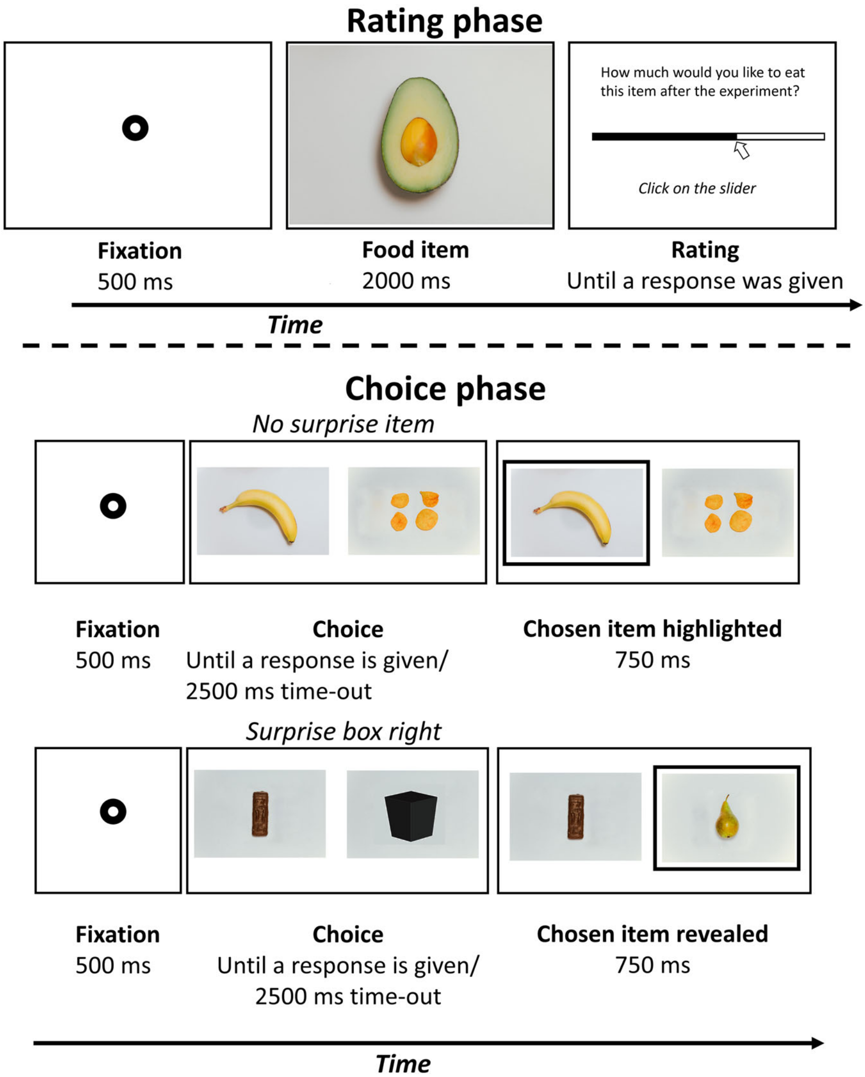

Figure 2. Experimental task. (A) The rating phase and (B) the choice phase.

Statistical analyses

The percentage of surprise choices and response times for surprise choices were compared for the novel and familiar condition with two paired-samples *t*-tests. We additionally checked whether there were any differences in number of surprise item choices between participants who were in the novelty room–first condition versus the familiar room–first participants. We ran regressions on the questionnaire subscales and their effects on surprise choices. To investigate response times during surprise item–present and surprise item–absent trials for the novel and familiar conditions, we ran a 2 × 2 repeated-measures ANOVA with novelty (novel; familiar) and trial type (surprise item–present; surprise item–absent) as within-subjects factors. Hunger was compared for the novel and familiar condition with a paired-samples *t*-test.

Stimuli and apparatus

The experiment was programmed in OpenSesame version 3.2.8[50] and presented on a 21-inch LCD monitor with a 120 Hz refresh rate and at a viewing distance of about 60 centimeters. The food stimuli consisted of all 40 stimuli from the Natural and Ultra-Processed Food (NUPF) database, with the

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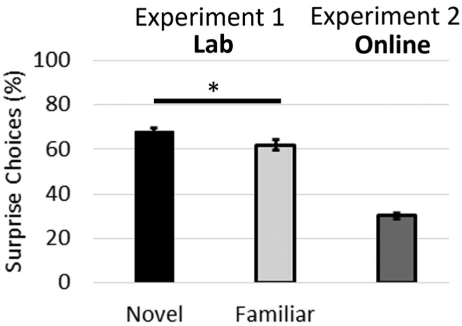

Figure 3. Surprise choices. The percentage of surprise choices on surprise item–present trials is shown for the novel and familiar condition in Experiment 1 and online Experiment 2. Error bars reflect the standard error of the mean.

food items photographed on a gray background. The NUPF database includes ratings on approachability (approach/avoid), desirability, popularity, healthiness, valence, arousal, and recognizability.[51] The stimuli were 1680 × 1050 pixels and presented during the rating phase in the center of the screen and during the choice phase to the left and right.

Results of Experiment 1

Experiment 1: proof-of-principle study in the lab

Figure 3 shows the % of surprise choices in the novel and familiar condition. Novelty influenced exploratory choices, with participants choosing a surprise item more often in the novel compared to the familiar condition, $t(16) = 2.65$, $P = 0.017$, $\eta^2 = 0.31$ (observed power = 0.703). Response times were similar for surprise choices in the novel and familiar conditions ($P = 0.625$), and also hunger was similar in the novel and familiar conditions (mean of novel = 3.41; *SD* of novel = 1.33; mean of familiar = 3.41; *SD* of familiar = 1.58; $P = 1.00$). The average participant scored $M = 15.37$ ($SD = 3.34$) on novelty seeking and $M = 10.32$ ($SD = 2.38$) on BIS. On the BAS subscales, average scores were $M = 8.89$ ($SD = 2.45$) for drive, $M = 8.26$ ($SD = 2.2$) for fun seeking, and $M = 7.95$ ($SD = 1.65$) for reward responsiveness. Regarding correlations between the questionnaire scales, hunger, and surprise choices, BAS fun seeking correlated negatively with the novelty-seeking trait, while hunger was negatively correlated with BAS fun seeking. BAS drive and BAS reward responsiveness were positively correlated, as were BIS and BAS reward responsiveness (Table 1).

We could not detect any differences between novelty-first and familiarity-first participants ($F(1,\ 16) = 1.299,\ P = 0.271$). We tested whether hunger had an effect on surprise item choices. Hunger affected neither the number of surprise choices made in the novel ($b = 0.696,\ 95\%\ \text{CI} = [-1.850; 3.241],\ P = 0.57$) nor the familiar ($b = -1.730, 95\%\text{CI} = [-4.039;\ 0.579], P = 0.132$) condition. The novelty-seeking trait did not affect the number of surprise choices made in either the familiar ($b = 0.60,\ 95\%\ \text{CI} = [-0.5;\ 1.71],\ P = 0.27$) nor novel condition ($b = 0.70,\ 95\%\ \text{CI} = [-0.293; 1.7],\ P = 0.16$).

Results from models predicting exploratory choices (i.e., percentage of surprise item choices) using BIS/BAS scores are reported in Table 2. Note that these were entered into separate regressions to avoid multicollinearity and estimate the individual predictors' effects. Results from a general model with all predictors are reported in Table 3.

It was further investigated whether response times differed for the different novelty and surprise item–present or –absent conditions. Whether a surprise option was present or not influenced response times, with faster responses on surprise item–present than surprise item–absent trials ($F(1, 17) = 5.15$, $P = 0.037$, $\eta^2 = 0.23$). Novelty of the environment did not influence response times ($P = 0.125$), nor did novelty and trial type interact ($P = 0.796$).

Methods for Experiment 2 (online experiment)

To identify additional factors influencing exploratory behavior, we extended our proof-of-principle experiment by creating an online adaptation of the experiment and collecting additional data regarding individuals' novelty-seeking trait, action radius, and social interactions during a COVID-19 lockdown. Data for this experiment were collected between October and November 2020.

Participants

For this experiment, there were 135 participants who volunteered. The final sample included 87 participants (49 females, 38 males; mean age = 34.5 (SD = 12.9), range 19–69; median = 33; skew-

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Table 1. Correlations between novelty seeking scores, hunger, BAS drive, BAS fun seeking, BAS reward responsiveness, BIS, and the percentage of surprise items chosen

	Surprise choices	Novelty seeking	Hunger	BAS drive	BAS fun seeking	BAS reward responsiveness	BIS
Surprise choices							
Novelty seeking	0.350						
Hunger	0.143	−0.005					
BAS drive	0.338	−0.339	0.181				
BAS fun seeking	−0.032	−0.427*	0.434*	0.293			
BAS reward responsiveness	0.324	−0.140	0.032	0.579**	0.360		
BIS	0.256	0.221	−0.227	0.362	−0.102	0.548**	

NOTE: Values are Pearson correlation coefficients.
*$P < 0.05$. **$P < 0.01$.

ness = 0.9; kurtosis = 0.26). Participants recruited through Mturk ($n = 75$) received 1.50 USD and participants recruited through SONA systems of Leiden University or social media platforms ($n = 60$) either received course credit or 3.50 Euro as compensation. Criteria for inclusion via MTurk were > 95% HIT approval rate and location of origin either in Europe (e.g., Norway, Belgium, or the Netherlands) or an English-speaking country (e.g., the United States, New Zealand, or Australia). All completed the task online. Compensation was both in line with the standard rate for experimental studies at the Faculty of Social Sciences at Leiden University and the typical MTurk rate. Again, ethical approval was obtained from the CEP ethics committee of the Faculty of Social and Behavioural Sciences at Leiden University. The study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Stimuli and apparatus

The same pictures of food items were used as in the lab experiment. The experiment was programmed in OpenSesame version 3.2.8,[50] hosted on a JATOS server, and supported by OSweb during runtime. Participants could run the online task on their own laptop or PC using a browser (e.g., Firefox, Chrome, and Safari were supported).

Procedure

The experimental procedure was the same as in the lab experiment, but with a few exceptions. At the beginning of the task, participants also gave a happiness rating on a 9-point Likert scale, including a visual analog scale with self-assessment manikins.[52] In the online task, participants made 80 choices during the choice phase and a surprise item was now present in 50% of the trials. In addition, participants filled out a newly created questionnaire, including 15 obligatory questions and three conditional subquestions (see File S1, online only): two questions regarding lockdown restrictions, five questions regarding social interactions (+ 1 subquestion), six questions regarding action radius (+ 2 subquestions), one question on feelings of isolation, and one on recent gaming activity. Filling out these questions took 4–5 min on average.

Statistical analyses

Response times for surprise items and no-surprise items on surprise item–present trials were investigated with a paired-samples t-test. In an

Table 2. Results from models using BIS/BAS subscale scores to predict the percentage surprise choices

		b	P	Lower bound CI	Upper bound CI
1	BAS drive	−0.091	0.807	−0.875	0.692
2	BAS fun seeking	0.090	0.831	−0.787	0.966
3	BAS reward responsiveness	−0.673	0.231	−1.822	0.475
4	BIS	−0.817	0.061	−1.675	0.041

Table 3. Regression model predicting the percentage surprise choices using novelty seeking scores, hunger, BAS drive, BAS fun seeking, BAS reward responsiveness, and the BIS

	b	*P*	Lower bound CI	Upper bound CI
(Constant)	2.097	0.698	−9.570	13.763
Novelty seeking	0.684	0.014	0.175	1.194
Hunger (novel)	−1.941	0.004	−3.102	−0.781
BAS drive	0.861	0.024	0.139	1.583
BAS fun seeking	0.925	0.026	0.132	1.717
BAS reward responsiveness	−0.789	0.157	−1.938	0.360
BIS	−1.248	0.009	−2.101	−0.396

exploratory analysis, we investigated whether the percentage of surprise choices changed over the duration of the experiment. As the randomization was done on the full list of trials, surprise trials were variably distributed over the choice phase for different participants. Therefore, we post-hoc divided the trials into four blocks, each with 20 consecutive trials. We then calculated the percentage of surprise choices per block on basis of the number of surprise item–present trials in that block per individual. The effect of block on the percentage of surprise choices was investigated with a repeated-measures ANOVA with Block (1; 2; 3; 4) as a within-subjects factor.

We used a new questionnaire, including 18 questions regarding lockdown regulations, social interactions, gaming activity, action radius, and subjective feelings of isolation during lockdown. For data reduction purposes and to identify underlying subscales, we performed a principal component analysis (PCA). As not all variables were on the same scale, we first Z-scored them. Then, we checked for correlations between variables: all correlations were above $r = 0.3$ and the determinant of the correlation matrix was above 0.00001. The Kaiser–Meyer–Olkin criterion suggested a sampling adequacy of 0.64. However, five variables showed individual factor loadings of below $|0.5|$, so we continued our PCA with only 13 questions (each with values above $|0.5|$), which increased the Kaiser–Meyer–Olkin criterion to 0.71.

We calculated the covariance matrix, and using the parallel and the scree criterion, the ideal number of components was determined to be 2. After checking for correlations between the components and choosing the correct rotation (above $r = |0.33|$ for oblique rotation, otherwise orthogonal rotation: in our case, orthogonal because $r = -0.17$), two main components were identified (see Results). We then ran regression analyses to model exploratory behavior, including two predictors (i.e., action radius and interaction) that were constructed on basis of the PCA results. Additional predictors were hunger, happiness, age, and novelty seeking. In the first step, we ran separate regression analyses per predictor. In the second step, we built an overall model, including all predictors to check for multicollinearity and to investigate the relative contributions of the predictors. We checked for outliers using Cook's distance and DFBeta's. Note that as the outcome measure was the percentage of surprise choices for surprise item present trials, the outcome variable is on a scale of 0–1, meaning that our regression weights are generally small.

Results of Experiment 2 (online)

Effects of experimental block and novelty

Figure 3 shows the % of surprise choices in Experiment 2. Whether a surprise item was present or not did not influence response times ($P = 0.877$). Experimental block influenced the percentage of surprise choices, $F(2, 297) = 2.72$, $P = 0.044$, $\eta^2 = 0.03$. A post-hoc linear effect analysis suggested that participants chose more surprise items at the end rather than the beginning of the task, $F(1,99) = 6.99$, $P = 0.010$, $\eta^2 = 0.07$. In an exploratory analysis, we tested whether exploration behavior as measured by the % surprise choices was correlated with the Exploratory Excitability subscale of the novelty-seeking scale but failed to find a relation (novel : $r = -0.18$, $P = 0.231$; familiar : $r = -0.33$, $P = 0.084$).

Using a PCA, we identified two main components. We found that one of the components had high loadings for questions related to action radius,

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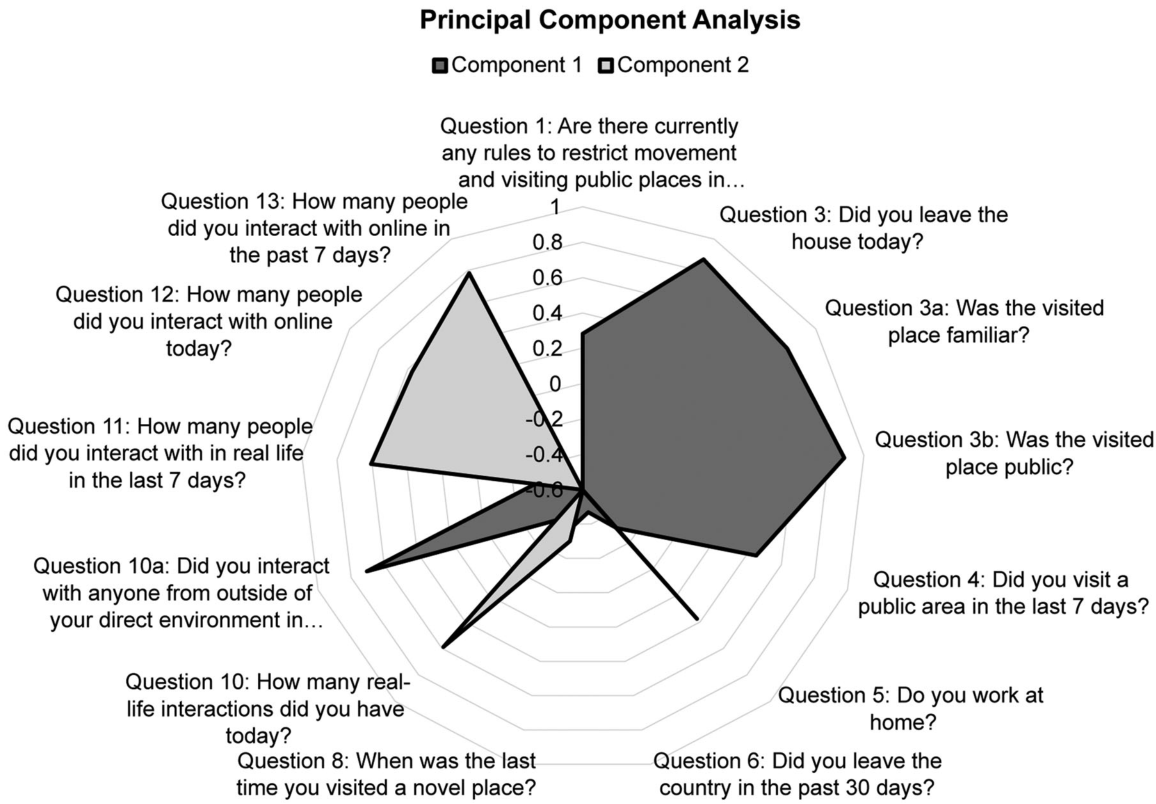

Figure 4. Factor loadings from the covariance matrix for the two main components. Loadings on the two main components are shown for the 13 questions (including three subquestions) included in the principal component analysis (PCA). One component included questions related to the action radius of people, while the other related more to social interactions. Questions 2, 7, 9, and 14 (see File S1, online only) were excluded due to low sampling accuracy. Note that some questions are abbreviated for display purposes. See File S1 (online only) for the original full-length questions.

while the other had high loadings for questions related to social interactions (online and in the real world; Fig. 4 and Table 4).

The PCA accounted for 47% of the variance. The first-component questions related to the *action radius* (e.g., whether people left the house today or visited a public area in the last 7 days) loaded highly, while the second-component questions related to social *interactions* (e.g., how many people they interacted with online and in the real world; Fig. 4 and Table 4) loaded highly.

On basis of the PCA results, we built scales using the component loadings, calculating composite scores for action radius and interaction. Only questions with factor loadings over |0.5| were included. This led to the inclusion of four questions for action radius and five for interaction, resulting in the following composite scores:

$$
\begin{aligned}
action\ radius &= 0.889 * x_{VisitedPublicAreaToday} \\
&\quad + 0.870 * x_{LeaveTheHouseToday} \\
&\quad + 0.805 * x_{VisitedPlaceFamiliar} \\
&\quad + 0.704 * x_{RealLifeInteractionsTodayOutsideFamily} \\
interaction &= 0.783 * x_{OnlineInteractionsPast7Days} \\
&\quad - 0.596 * x_{LeaveCountryInPast30Days} \\
&\quad + 0.573 * x_{OnlineInteractionsToday} \\
&\quad + 0.605 * x_{RealLifeInteractionsPast7Days} \\
&\quad + 0.588 * x_{RealLifeInteractionsToday}
\end{aligned}
$$

A regression analysis with action radius as a predictor suggested that people who reported

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Table 4. Component loadings table of the lockdown questionnaire

Variable	Component 1: Action radius	Component 2: Interactions
Question 1: Are there currently any rules to restrict movement and visiting public places in your country?	0.282	
Question 3: Did you leave the house today?	0.870	
Question 3a: Was the visited place familiar?	0.805	
Question 3b: Was the visited place public?	0.889	
Question 4: Did you visit a public area in the last 7 days?	0.449	
Question 5: Do you work at home?	−0.311	0.375
Question 6: Did you leave the country in the past 30 days?	−0.469	−0.596
Question 8: When was the last time you visited a novel place?	−0.391	−0.301
Question 10: How many real-life interactions did you have today?	−0.367	0.588
Question 10a: Did you interact with anyone from outside of your direct environment in real life today?	0.704	
Question 11: How many people did you interact with in real life in the last 7 days?	−0.329	0.605
Question 12: How many people did you interact with online today?		0.573
Question 13: How many people did you interact with online in the past 7 days?		0.783

NOTE: Some questions were abbreviated for display purposes. See File S1 (online only) for the original full-length questions.

more movements outside of the house made more exploratory choices ($b = 0.235$, 95% CI = [0.004; 0.074], $P = 0.031$). In a regression with interaction as a predictor, no effect of interaction on exploratory behavior was found ($P = 0.324$). For both models, see Table 5.

Age, hunger, happiness, and novelty seeking

In line with our expectations, we found that exploratory choices decreased with increasing age (no outliers identified; $b = -0.005$, 95% CI = [−0.010; −0.001], $P = 0.025$). In a separate regression model, we found that individuals who scored higher on the novelty-seeking trait made more exploratory choices than individuals who scored low on novelty seeking (no outliers identified; $b = 0.013$, 95% CI = [0.003; 0.022], $P = 0.011$). Hunger (7-point Likert scale: mean = 3.90; SD = 1.79) nor happiness (9-point Likert scale: mean = 6.74; SD = 1.67) were shown to predict exploratory choice behavior in separate models ($b = -0.003$, 95%CI = [−0.030; 0.025], $P = 0.846$ and $b = -0.005$, 95% CI = [−0.034; 0.025], $P = 0.758$ respectively).

Complete model

In a final model, we entered all six predictors of interest (action radius, interaction, age, novelty seeking, happiness, and hunger) into one regression model (Table 6). All variance inflation factors were between 1.10 and 1.52, suggesting that multicollinearity was low. The overall regression model was not significant ($F(6, 73) = 2.198$, $P = 0.053$. Nevertheless, novelty seeking showed an

Table 5. Regression models with action radius and interaction (based on the PCA-derived components) as predictors of the percentage of surprise items chosen

		β	t	P	VIF
1	(Constant)		5.050	0.000	
	Action radius	0.241	2.192	0.031	1.000
2	(Constant)		2.724	0.008	
	Action radius	0.240	2.075	0.041	1.094
	Interaction	−0.003	−0.023	0.982	1.094

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Table 6. Parameter values in the complete model

	β	t	P	VIF
(Constant)		0.951	0.345	
Action radius	0.221	1.921	0.059	1.144
Interaction	0.025	0.198	0.843	1.365
Happiness	−0.073	−0.642	0.523	1.102
Novelty seeking	0.239	2.043	0.045	1.185
Age	−0.114	−0.857	0.394	1.522
Hunger	0.083	0.720	0.474	1.156

additional contribution to the full model, with high novelty seekers making more exploratory choices than low novelty seekers, $b = 0.011$, 95% $CI = [0.0; 0.022]$, $P = 0.045$. None of the other predictors had a significant contribution (all Ps > 0.3); however, action radius showed a trend effect for individuals, with a larger action radius making more exploratory choices, $b = 0.035$, 95% CI $= [-0.002; 0.072]$, $P = 0.062$.

Behavioral differences

Finally, we looked at the differences in exploratory behavior, as operationalized by the percentage of surprise item choices, in the lab versus the online experiment. In both the novel and familiar labs, more exploratory choices were made than in the online experiment ($t(101) = 5.85$, $P < 0.001$ and $t(94) = 4.84$, $P < 0.001$, respectively).

Discussion

In the current study, we aimed to identify factors driving food-related exploratory behavior. In the first lab experiment, we used a new exploration–exploitation paradigm and a unique spatial novelty manipulation. Participants performed a food choice task with surprise options in a novel and a previously familiarized real-world environment, allowing us to investigate whether novelty would promote exploratory behavior. In a second experiment, which was carried out online, we aimed to extend the impoverishment literature in animals by investigating whether action radius and social interactions during a COVID-19 lockdown could predict exploratory behavior in humans. We further addressed other factors that could influence exploratory behavior, including internal states like hunger and happiness, and individual differences, including the novelty-seeking trait and age. In our tasks, we used the percentage of chosen surprise items as a measure of exploratory behavior. In line with a novelty bonus, we observed that participants made more exploratory choices when in a novel rather than familiar lab (Experiment 1). In Experiment 2, we found that a smaller action radius was associated with fewer exploratory choices, exploratory behavior declined with age, and high novelty seekers made more exploratory choices than low novelty seekers.

To our knowledge, this is the first study to investigate the effects of *spatial novelty* on exploratory behavior in a food choice task in humans. In Experiment 1, we observed that participants chose the surprise item with a higher probability when in the novel rather than the familiar environment. This finding is in line with studies in animals that have suggested that animals are more willing to take food-related "risks" when in a novel rather than familiar environment.[1] Our finding is also in line with predictions made by models regarding the exploration–exploitation trade-off,[2] and computational models that have suggested that novelty promotes exploratory behavior through novelty bonuses.[8] Novel environments typically offer more novel opportunities, and our finding suggests that novelty of the environment itself nudges people toward more exploratory rather than exploitative behavior. This is also in line with neuroimaging studies that have found that novelty can activate mesolimbic dopaminergic pathways in the brain that are also associated with novelty bonuses and exploratory behavior.[7–9,53–55]

The literature on neophobia suggests that people have a reluctance to try novel food items.[56,57] Findings from the current study suggest that novelty of the environment may help override this preference for familiar food items, as participants chose

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more unknown items in a novel rather than familiar environment (Experiment 1). Generalization of our findings to neophobia should be made with caution, though, as all food items in our task were presented to the participants before the experiment on a menu with food labels, and the food items had a high recognizability score, as was quantified in the NUPF database from which our stimuli were taken. Instead, our findings suggest that people may be more inclined to choose an option for which the outcome is unknown when they are in a novel rather than familiar environment. Follow-up studies could aim to investigate whether the effects of exposure to a novel environment also generalize to novel, rather than unknown, options (i.e., that more novel options are chosen in a novel rather than familiar environment).

The sample from the online task (Experiment 2) had a larger age range, including individuals from ages 19 to 69, allowing us to investigate exploratory behavior across the life span. Our findings suggested that increasing age was associated with fewer exploratory choices. This is consistent with previous findings that older adults are more likely to exploit their current resources before seeking new ones.[58] In this study, older adults would try to use books or websites they are already familiar with to answer a question before searching for new books or websites. These findings suggest that elderly tend to exploit known options rather than explore new ones, which is in line with increased risk aversion in elderly.[21] This pattern of results may be explained by the age-related degeneration of the dopaminergic pathway, leading to a reduction in novelty or exploration bonuses in older individuals.[11,25,26] Potentially, novelty exposure could promote exploratory choices in older individuals, but this still needs to be addressed in future studies.

Although the full model was not significant, both a model with novelty seeking as a single predictor and the full model with all predictors suggested that high novelty seekers made more exploratory choices. This is in line with a previous study that linked the novelty-seeking trait to striatal activations in the human brain and exploratory behavior in a value-based choice task.[7] In the lab experiment, we did not find novelty seeking to be a predictor of exploratory choices, but this could be due to the limited sample size in this experiment, while the larger sample in Experiment 2 showed more individual variability. The online experiment also had a more even sex distribution than the lab study, which is a commonly reported finding in university-based studies. However, since a meta-analysis has shown that there are no sex differences in novelty seeking, we chose not to investigate these differences further.[59]

Experimental work on environmental impoverishment in humans is scarce due to obvious ethical concerns. The COVID-19–related regulations and restrictions created a unique possibility to investigate the effects of reduced action radius or social interactions on exploratory behavior. Our findings are in line with studies that have suggested that environmental impoverishment can lead to reduced exploration.[45,60] We found that a lower action radius, potentially caused by COVID-19 lockdown regulations, was associated with less exploratory behavior on our food choice task.

It is possible that the relationship between action radius and exploratory behavior is not a causal one, and we cannot draw inferences about the direction of the effect. A larger action radius may have resulted in individuals making more exploratory choices; however, also the reverse may have happened, with individuals staying at home more having a smaller action radius because they have lower exploratory excitability to begin with. However, we failed to find a relationship between exploration on our task and the exploratory excitability scale of the novelty-seeking questionnaire.

In Experiment 2, we observed that participants chose more surprise items toward the end compared to the beginning of the choice phase. This may be due to increasing boredom on later trials. Some participants in the lab experiment indicated that, even though they were instructed about this, they first were not sure what would be hidden in the box, but that after a while they realized it always contained food items. Potentially, a reduction in uncertainty about the possible contents led participants to choose the surprise item more often toward the end of the experiment.

In Experiment 1, food items were presented to the participants, and they were told that they would receive one of their choices after the experiment, making decision making a relevant task aspect. However, in the online Experiment 2, the choices were hypothetical. This may have changed the way the task was perceived and could potentially have

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influenced response strategies (e.g., relying more on heuristics). That participants used different strategies is also suggested by the difference in the percentage of exploratory choices between the two experiments, with more exploratory choices in the lab than in the online experiment. However, the two tasks included different percentages of surprise item–present trials, which may also have influenced exploratory behavior differently between the two tasks.

Although we expected that hunger and happiness would be associated with more exploratory behavior, we did not find evidence for such relationships in our experiments: hunger and happiness were not associated with exploratory behavior in our models. The findings of no effect of hunger on exploration behavior are in contrast with previous findings,[30–32] while the lack of a happiness effect is in line with previous work.[19,20] A potential reason we did not observe effects of hunger may be that we only used self-report scales, with most people reporting hunger to be around the middle of the scale (with few extremes). It may, therefore, be recommended to experimentally control hunger (e.g., by asking participants to participate fully satiated or not eat for a few hours before the experiment). To further address the effects of mood, it may be recommended to follow up the current findings by manipulating affective state via mood induction.[61] Importantly, however, hunger reports were similar in the novel and familiar conditions in Experiment 1, suggesting that the effects of novelty could not be explained by differences in hunger.

Other factors that may have influenced the exploratory food choices in our task, but that we did not consider in the current study, are body indices (such as body mass index (BMI) or body fat mass), impulsivity, and risk-taking.[62] Hedonic aspects of eating behavior, but also overeating, have been linked to reward circuits in the brain, most notably the dopaminergic system.[63] As such, individual differences in impulsive behavior linked with overeating could potentially confound the effects of novelty, which are also associated with dopaminergic pathways. Previous work has also linked a BMI to impulsivity, and a higher body fat assessment (BFA) has been associated with risky decision making.[64] As exploration involves more risk-taking,[18] a higher BMI/BFA may, thus, be more strongly associated with exploratory rather than exploitative behavior.[65] Therefore, it may be recommended that future studies investigating exploratory food choices also take body indices or other measures of risk-taking into account.

A limitation of Experiment 1 was that we were only able to test 18 participants due to changing COVID-19 restrictions during the testing period. Although all participants were part of both the novel and familiar conditions in our within-subjects design, this relatively small sample may have led to a slightly underpowered design (observed power: 0.701) and a potential failure to observe other effects.

Despite potential limitations, findings from Experiment 1 suggested that spatial novelty can promote exploratory behavior. In Experiment 2, we found that age was a predictor of exploratory behavior, with increasing age associated with fewer exploratory choices. Also, the novelty-seeking trait predicted exploration, with high novelty seekers making more exploratory choices than low novelty seekers. Interestingly, recent activity outside the house (i.e., action radius) also predicted the number of exploratory choices. As one of the first studies on human behavior in deprived environments, our study suggests that both novelty and a larger action radius are associated with exploratory behavior. These findings are in line with previous findings in animals and predictions derived from computational models, suggesting that a novelty bonus may drive exploratory decision making. This study is the first to identify interindividual and environmental factors associated with food-related exploratory behavior in humans, suggesting that a novelty bonus may drive exploration, while a lower action radius is linked to less exploration.

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Author contributions

T.M.P. was involved in conception, data acquisition, analysis, interpretation, and writing of the manuscript. J.S. was involved in conception, design, data analysis, interpretation, writing of the manuscript, and revising its intellectual content. Both authors accept responsibility for the integrity of the data analyzed.

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Supporting information

Additional supporting information may be found in the online version of this article.

File S1. Lockdown questionnaire

Competing interests

The authors declare no competing interests.

Peer review

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