Adaptation to recent outcomes attenuates the lasting effect of initial experience on risky decisions

Andrea Kóbor [1,+,*], Zsófia Kardos [1,2,+], Ádám Takács [3], Noémi Éltető [4], Karolina Janacsek [5,6,7], Eszter Tóth-Fáber [8,5,6], Valéria Csépe [1,9], Dezso Nemeth [6,5,10,*]

[1]: Brain Imaging Centre, Research Centre for Natural Sciences, *Magyar tudósok körútja 2., H–1117, Budapest, Hungary*
[2]: Department of Cognitive Science, Budapest University of Technology and Economics, *Egry József utca 1., H-1111, Budapest, Hungary*
[3]: Cognitive Neurophysiology, Department of Child and Adolescent Psychiatry, Faculty of Medicine of the TU Dresden, *Fetscherstraße 74, 01307 Dresden, Germany*
[4]: Max Planck Institute for Biological Cybernetics, *Max-Planck-Ring 8, 72076 Tübingen, Germany*
[5]: Institute of Psychology, ELTE Eötvös Loránd University, *Izabella utca 46., H–1064, Budapest, Hungary*
[6]: Brain, Memory and Language Research Group, Institute of Cognitive Neuroscience and Psychology, Research Centre for Natural Sciences, *Magyar tudósok körútja 2., H–1117, Budapest, Hungary*
[7]: Centre of Thinking and Learning, Institute for Lifecourse Development, School of Human Sciences, Faculty of Education, Health and Human Sciences, University of Greenwich, *Old Royal Naval College, Park Row, 150 Dreadnought, SE10 9LS, London, United Kingdom*
[8]: Doctoral School of Psychology, ELTE Eötvös Loránd University, *Izabella utca 46, H–1064, Budapest, Hungary*
[9]: Faculty of Modern Philology and Social Sciences, University of Pannonia, *Egyetem utca 10, H–8200, Veszprém, Hungary*
[10]: Lyon Neuroscience Research Center (CRNL), Université de Lyon, *Centre Hospitalier Le Vinatier – Bâtiment 462 – Neurocampus 95 Boulevard Pinel 69675 Bron, Lyon, France*

+: These authors contributed equally to this work.

*: Corresponding authors:

Andrea Kóbor
Brain Imaging Centre, Research Centre for Natural Sciences
Magyar tudósok körútja 2., H–1117, Budapest, Hungary
E-mail: kobor.andrea@ttk.hu; Phone: +36 1 382 66 15

Dezso Nemeth
CRNL – Lyon Neuroscience Research Center, Université Claude Bernard Lyon 1
CRNL – Centre Hospitalier Le Vinatier – Bâtiment 462 – 95 Bd Pinel – 69675 Bron Cedex – Lyon, France
E-mail: dezso.nemeth@univ-lyon1.fr; Phone: +33 4 81 10 65 46

Abstract

Both primarily and recently encountered information have been shown to influence experience-based risky decision making. The primacy effect predicts that initial experience will influence later choices even if outcome probabilities change and reward is ultimately more or less sparse than primarily experienced. However, it has not been investigated whether extended initial experience would induce a more profound primacy effect upon risky choices than brief experience. Therefore, the present study tested in two experiments whether young adults adjusted their risk-taking behavior in the Balloon Analogue Risk task after an unsignaled and unexpected change point. The change point separated early "good luck" or "bad luck" trials from subsequent ones. While mostly positive (more reward) or mostly negative (no reward) events characterized the early trials, subsequent trials were unbiased. In Experiment 1, the change point occurred after one-sixth or one-third of the trials (brief vs. extended experience) without intermittence, whereas in Experiment 2, it occurred between separate task phases. In Experiment 1, if negative events characterized the early trials, after the change point, risk-taking behavior increased as compared with the early trials. Conversely, if positive events characterized the early trials, risk-taking behavior decreased after the change point. Although the adjustment of risk-taking behavior occurred due to integrating recent experiences, the impact of initial experience was simultaneously observed. The length of initial experience did not reliably influence the adjustment of behavior. In Experiment 2, all participants became more prone to take risks as the task progressed, indicating that the impact of initial experience could be overcome. Altogether, we suggest that initial beliefs about outcome probabilities can be updated by recent experiences to adapt to the continuously changing decision environment.

Keywords: Balloon Analogue Risk Task (BART), behavior adjustment, decision making, initial luck, recency effect, risk-taking behavior, primacy effect

Introduction

Decision making is supported by generating predictions about the probability of upcoming events. Many of these predictions are guided by inferences based on prior experiences with a similar situation or early experiences with the current situation. Considering risky choices, if we learned that regulations were moderate and had the repeated experience that driving beyond the speed limit did not end in negative consequences, we would be more likely to continue this behavior. However, in the case of stricter regulations, this habitual choice behavior becomes disadvantageous and should be overcome. Adaptation to the newly encountered regulations is probably gradual but takes an unknown amount of time, depending on several factors. Accordingly, this study investigated in an experience-based risky decision-making paradigm whether initial experience or the combination of initial and recent experiences had stronger impact on risk-taking behavior after an unsignaled change in outcome probabilities.

It has long been investigated how and under which conditions belief updating occurs in probability decisions [1]. For instance, the temporal order of information seems to play a considerable role in uncertain decision-making situations where decisions rely on experience [2]. According to the anchoring and adjustment heuristic, initial beliefs based on limited observations serve as a reference point that is adjusted as information accumulates. The effect of initial anchor is probably long-lasting since adjustments are usually insufficient and biased toward the initial values [3]. Meanwhile, the complexity of the task, the amount of new evidence, and the response mode (responding after integrating each piece of evidence or after the presentation of all pieces of evidence) have been shown to influence the effect of information order. Thus, there are conditions under which primacy, recency, or no order effects, respectively, are more to likely occur in probability decisions [1].

Evidence from studies targeting or modeling real-life risky situations supports the combination of both primacy and recency effects. Based on survey data, it was shown that those who had experienced great macroeconomic shocks became financially more risk averse in their later lives; for instance, they were less likely to participate in the stock market [4]. Although recent experiences received more weight than more distant ones, the impact of experiences that had happened even years earlier remained significant. This so-called depression baby hypothesis has also been tested with simulated experimental stock market experiments where participants hypothetically invested in safe (cash deposit account) and risky (stock index fund) options [5]. These experiments manipulated whether participants learned from experience (played the investment game) or from symbolic description (only studied graphs of the initial period) and whether the data included or excluded initial macroeconomic crisis (negative shock) or boom (positive shock). Depending on the valence of the initial shock, participants who learned from experience took less or more risks than those who learned from description (cf. [2,6]). Importantly, the most recent experience also played a role in participants' investment behavior that was reactive to local fluctuations in stock prices, irrespective of experimental manipulations.

Other studies of sequential decision making indicate the prominence of recency effect [7]. Due to the continuous tracking of the recent outcomes, in nonstationary stochastic environments, individuals accurately estimated the underlying probabilities and quickly updated their estimates if there was a change in these probabilities [8-10]. The prominent impact of recently observed outcomes was also demonstrated for the sequential sampling of gambles and their valuation [11,12].

The studies described so far suggest that individuals could successfully use recently observed evidence to adapt to the changing environment. However, fast adaptation to initial payoff probabilities followed by only slow adaptation to changes in these probabilities was also found, especially if the history summarizing previous outcomes was explicitly provided to participants [13,14]. In addition, as demonstrated in a hypothetical stock market game, the initially established decision strategy was retained even though it became no longer optimal [15]. A hint about the change, monetary incentives, or transfer to another task with the same deep structure but different surface could not adequately support the update of this original decision strategy. Therefore, depending on the decision situation, belief updating could also be difficult or completely missing.

Among tasks requiring sequential decisions, the Balloon Analogue Risk Task (BART) has been a widely used laboratory measure because its structure and appearance mimics naturalistic risk taking [16-19]. This task requires sequential decisions on risk in the form of inflating virtual balloons on a screen. Participants are told that each balloon pump is associated with either a reward (balloon inflation with increased score) or a loss (balloon burst with lost score). However, the outcome of each successive pump (inflation vs. burst) and the probability distribution determining the outcome are unknown to participants. Thus, the BART measures decision making under uncertainty/ambiguity [20-22]. Due to repeated sampling, participants could learn about the payoff structure of the task in a trial-and-error manner to maximize the total reward. Thus, similarly to the paradigms in the above-referred studies, the BART is a “decisions from experience” task [2].

To our knowledge, two studies investigated whether beliefs about outcome probabilities are updated if these probabilities change considerably after a certain balloon in the BART. The study of Koscielniak, et al. [23] showed that initial good luck and bad luck modulated subsequent adaptation. After the unlucky series (bursts on the first three balloons after three, four, and one pumps), the number of balloon inflations gradually increased in the following phases of the task. After the lucky series (bursts on the first three balloons after 25, 27, and 28 pumps), their number were higher only in the first phase following manipulation and decreased in the middle and final phases. However, the difference between the bad luck and good luck conditions remained persistent in every phase. The study of Bonini, et al. [24] used five early losses (bursts at the first, second, third, second, and first pumps) in a modified BART and contrasted the observed balloon inflations with that of an original BART. Healthy control participants showed a lower number of balloon inflations across the remaining balloons of the modified BART as compared with the original BART. As the task progressed, they increased the number of balloon inflations and this increase was steeper in the modified BART. In sum, although early negative events decreased overall risk taking (i.e., fewer balloon inflations), experience with more balloons still increased it gradually [4,5].

In contrast to these studies, risk-taking behavior was influenced by positive or negative economic forecast (i.e., predictive message that the probability of balloon bursts would decrease or increase in the next task block) even without changing the payoff structure of the BART [25,26]. Similarly, framing effects (inflate balloons to gain reward or avoid losing reward) without actual structural changes also influenced risk-taking behavior in the BART [27,28]. Considering the former and latter group of studies, it is possible that if no explicit information were provided about the changes in outcome probabilities, the cognitive processes underlying dynamic decision making in the BART would remain flexible. This flexibility would support the smooth adjustment of behavior to the new properties of the environment. Nevertheless, previous studies manipulated only the very first trials by using extremely high or low balloon tolerances. Therefore, it has not been systematically tested whether longer initial experience might result in more persistent primacy effect and weaker subsequent adaptation to the changed payoff structure than shorter experience, in line with the existing accounts (cf. [1,4,13]).

Accordingly, the present study investigated how different lengths of initial experience influenced risk-taking behavior during sequential sampling of outcome probabilities without signaling the change in the payoff structure. In Experiment 1, the first five (short manipulation) or ten (long manipulation) balloons of the task consisting of 30 balloons were manipulated to induce negative or positive initial experience. While the results of Experiment 1 suggested that different lengths of both negative and positive initial experience could be overcome to a limited extent, two questions remained open. First, without baseline experience, it was not measured whether early positive and negative manipulations led to the intended experiences (cf. [25]). Second, because the underlying payoff structure changed at different times across the long and short experimental conditions, participants encountered a slightly different series of unbiased balloons after the manipulated phase. Therefore, the potential to change risk taking on the unbiased balloons was differently constrained across the length conditions. To address these issues and to check whether findings of Experiment 1 are reproducible, in Experiment 2, we included baseline experience beyond positive and negative experience, and separated the manipulated phase from the subsequent phase. The payoff structure of the subsequent phase that was used to quantify the update of risk-taking behavior was identical across the experimental conditions.

In Experiment 1, if initial experience was long, we hypothesized its profound and constraining effect on risk-taking behavior without update (i.e., more/less balloon inflations after positive/negative experience, cf. [1,5]). In contrast, we expected a more limited primacy effect if initial experience was short. In the latter case, initial and more recent experiences would be combined, which yields similar risk-taking behavior later in the task, irrespective of the valence of initial experience [29]. In Experiment 2, we hypothesized that the effect of initial experience would be carried over to the subsequent task phase [30,31]. Since the separate manipulated phase of Experiment 2 consisted of the same number of balloons as the long condition of Experiment 1, we expected to find similar results. Having been aware of the results of Experiment 1, after positive and negative experience in the initial phase, we hypothesized the presence of primacy effect that could be, at least partially, overcome (i.e., balloon inflations would be overall less/more after negative/positive experience but could increase/decrease as the task progresses). After the baseline experience, we expected to find a relatively constant risk-taking behavior that would be similar between the initial and subsequent task phases. In addition, we also expected that negative experience would be more different from baseline than positive experience in terms of balloon inflations (cf. [26]).

Experiment 1

In Experiment 1, using a modified BART, we manipulated the first five or ten balloons out of the 30 balloons. We created lucky and unlucky runs of trials by providing the possibility to inflate the balloons to a larger size (lucky condition) or to experience frequent balloon bursts even after relatively few balloon pumps (unlucky condition). We crossed these conditions with the length of the initial experience (long condition: ten balloons vs. short condition: five balloons) to check whether the length of exposure to lucky or unlucky events differently influenced subsequent risk-taking behavior. These manipulations were based on the assumption that participants tended to gain some experience with the task in terms of action-outcome mapping (i.e., they tended to inflate the balloons instead of being risk-averse, [21,32]), which would have enabled them to experience lucky and unlucky runs of events.

Method

Participants. Eighty healthy young adults took part in Experiment 1, 20 in each experimental condition. As we used a between-subjects design, one participant performed only one experimental condition. This contrasts with previous studies testing the effect of initial experience or framing in the BART [23,24,26,28]. Although between-subjects designs involve known disadvantages (e.g., individual variability across experimental groups), they limit carryover effects that might originate from the complex experimental manipulation used here (i.e., luck and length). While the above-mentioned previous studies could not provide directly applicable effect size measures for the current between-subjects design, based on their findings, an f(U) effect size of at least 0.25 could be expected for the adjustment of the initial luck effect (i.e., interaction between task phase and condition). According to a power analysis with G*Power software version 3.1.9.4; [33], with an alpha level of 0.05 and a desired power level of 0.85, the required total sample size would be at least 60 participants. Therefore, our sample of 80 participants was sufficiently large to detect differences in the adjustment of risk-taking behavior across the conditions.

Participants were students from different universities in Budapest and young adult volunteers. All participants had normal or corrected-to-normal vision and none of them reported a history of any neurological and/or psychiatric condition. All of them provided written informed consent before enrollment. The experiment was approved by the United Ethical Review Committee for Research in Psychology (EPKEB) in Hungary and by the research ethics committee of Eötvös Loránd University, Budapest, Hungary; and it was conducted in accordance with the Declaration of Helsinki. As all participants were volunteers, they were not compensated for their participation. Descriptive characteristics of participants randomly assigned to the four different experimental conditions in Experiment 1 are presented in Table 1.

Stimuli, design, and procedure. The appearance of the BART was the same as described in previous studies [34-38]. This version of the task was written in Presentation (v. 18.1, Neurobehavioral Systems). According to the instructions, participants were asked to achieve as high score as possible by inflating empty virtual balloons on the screen. They were also told that they were free to pump as much as they felt like, however, the balloon might burst. After each successful pump, the accumulated score on a given balloon (temporary bank) simultaneously increased with the size of the balloon. Instead of further pumping the balloon, participants could have finished the actual balloon trial and collected the accumulated score, which was transferred to a virtual permanent bank. Two response keys on a keyboard were selected either to pump the balloon or to finish the trial. There were two possible outcomes as results of a pump: The size of the balloon together with the score inside increased (positive feedback) or the balloon burst (negative feedback). The balloon burst ended the actual trial, and the accumulated score on that balloon were lost, but this negative event did not decrease the score in the permanent bank.

One point was added to the temporary bank for the first successful pump, two for the second (i.e., the accumulated score for a given balloon was 3), three for the third (i.e., the accumulated score was 6), and so on. Five information chunks persistently appeared on the screen during the task: (1) the accumulated score for a given balloon in the middle of the balloon, (2) the label "Total score" representing the score in the permanent bank, (3) the label "Last balloon" representing the score collected from the previous balloon, (4) the response key option for pumping the balloon and (5) the other response key option for collecting the accumulated score. After collecting the accumulated score and ending the balloon trial, a separate screen indicated the gained score. The feedback screen, indicating either the gained score or a balloon burst, was followed by the presentation of a new empty (small-sized) balloon denoting the beginning of the next trial.

Although the surface structure of the present task was consistent with the original version [17] and with those described in our previous studies [35,38], the deep structure was modified. In the former versions, each successive pump not only increases the chance to gain more reward but also the probability of balloon burst and the accumulated reward to be lost. Therefore, the optimal choice is to inflate the balloon until a certain size, after that, further pumps are disadvantageous. This way, as Schonberg, et al. [18] pointed out, "increased risk is confounded with varying expected values" (p. 17) in the BART. In the present modified version, the probability of a balloon burst was zero until a certain threshold (maximum number of successful pumps) but it was one for the next pump for a similar design, see [39]. Although this design does not allow us to quantify how participants handle the dynamic change of burst probabilities within each balloon (across pumps), the risk level increases with each successive pump. Particularly, participants must consider the possibility to gain even more reward (the added points increase with each pump, see above) or to lose the already accumulated reward [40,41]. Due to these modifications, the effect of positive and negative feedback and the sense of luckiness might become more emphasized, as balloon bursts could be experienced at various balloon sizes (see below).

We would like to note that the terms "lucky" and "unlucky" were used to be consistent with the study of Koscielniak, et al. [23] and to simplify the nomenclature of the design and the description of the results. As the subjective sense of luck or bad luck was not explicitly tested, no information was available on whether participants considered themselves as lucky or unlucky. More importantly, in all conditions, participants were not informed about the structure of the task and the change from the initial phase to the remaining phase in the maximum number of successful pumps. With repeated balloon inflations, they had the opportunity to experience the payoff structure. Therefore, as the original version, even this task measured decision making under uncertainty and decisions from experience [2]. We should nevertheless note that as the structure of the task considerably differed from that of the original BART, caution is needed when the current results are compared to those with the original task version.

Participants had to inflate 30 balloons in the task. We chose specific values for the *maximum number of successful pumps* on each of the 30 balloons. The maximum number of successful pumps means that if a participant inflated the given balloon one pump further, the balloon burst. The maximum number of successful pumps for each balloon in each condition is presented in Table 2. These values were fixed across participants but differed across conditions.

Regarding the initial balloons, in the *lucky long* condition, the maximum number of successful pumps for each of the first ten balloons was determined by a fixed variation of 12 and 15. In the *lucky short* condition, the maximum number of successful pumps for each of the first five balloons was 15 (same for all five initial balloons). In the *unlucky long* condition, for each of the first ten balloons, this was a fixed variation of four and five. In the *unlucky short* condition, for each of the first five balloons, this was five (same for all five initial balloons).

We also determined the maximum number of successful pumps for each balloon in the remaining 20 or 25 balloons (after initial balloons): These were identical to one another between the equal-length conditions (i.e., lucky vs. unlucky long conditions and lucky vs. unlucky short conditions, see Table 2) and across participants, as indicated above. The fixed series of values were a random sequence of integers generated from a uniform distribution between three and 15 in Matlab 8.5 (MathWorks Inc.). We had chosen this interval between minimum and maximum values to ensure that the remainder of the experiment was different from the initial phase and balloons could be, on average, inflated up to a “medium” size.

There was no significant difference in the mean of the maximum number of successful pumps – calculated for the whole task – between the lucky long (M = 10.66, SD = 3.44) and lucky short (M = 10.03, SD = 3.47) conditions (p = .412) and between the unlucky long (M = 7.60, SD = 3.28) and unlucky short (M = 8.36, SD = 3.05) conditions (p = .309). Hence, the length of the initial phase did not change the overall potential of risk taking. Lucky long and unlucky long conditions differed significantly (p < .001) in the mean of the maximum number of successful pumps, so did lucky short and unlucky short conditions (p = .023).

Data analyses. To evaluate the effect of initial experience on risk-taking behavior, we performed linear mixed-effects analyses on the number of pumps on each balloon that did not burst as the dependent variable. This adjusted pump number is a conventionally used index in the BART literature [17,23,42,43]. Although accumulating evidence indicates that risk-taking propensity or risk preferences measured by self-report questionnaires and by behavioral measures are poorly correlated [6,39,44], in line with the BART literature, we considered the adjusted pump number as a measure of risk taking (cf. [45]). The advantage of using linear mixed-effects models is that they could account for the nonindependence of observations nested within participants (i.e., balloon pumps are repeated measures observations within participants). In addition, the dependent variable (number of pumps) does not have to be aggregated at the level of participants, which could yield less unexplained variance and higher statistical power.

To determine more clearly how long the effect of initial experience would persist, each balloon was assigned to a five-balloon-long time bin of the task. Although dividing the task into five-balloon-long bins might seem arbitrary, it is in accordance with the length of each manipulation (equal to the short ones, half of the long ones). We found easier to interpret the results based on bin-wise analyses that has also been frequent in the BART literature (e.g., [21,24,46]). Therefore, further linear mixed-effects analyses were performed on the number of pumps on balloons that did not burst while considering the balloons' bin-wise assignment. Importantly, to account for the effect of time bin, no aggregation of the dependent variable (number of pumps) was needed at the level of bins.

The balloon-wise and bin-wise linear mixed-effects analyses were performed on the number of pumps on *remaining* (unbiased) balloons that did not burst in the equal-length conditions. Thus, separate models were fit to the data of the long-manipulation conditions (lucky and unlucky long) and that of the short-manipulation conditions (lucky and unlucky short). In the long-manipulation conditions, the remaining phase of the task consisted of 20 balloons or four bins, in the short-manipulation conditions, the remaining phase consisted of 25 balloons or five bins. The tolerances of the remaining balloons were the same across the equal-length conditions, but these values were shifted across the different-length conditions. (Particularly, tolerance values were the same between Balloons 11–30 in the long conditions and between Balloons 6–25 in the short conditions, see Table 2). Therefore, the possibility to inflate a balloon during the remaining phase was differently constrained across the conditions, which warranted the separate analyses of the temporal change in risk-taking behavior after the end of initial manipulation.

After these analyses, linear mixed-effects models including all experimental factors were also fit to the *entire task* with 30 (manipulated and unbiased) balloons or six bins. We found the latter analyses reasonable to test the potential effect of length manipulation on pumping behavior and its adjustment.

All analyses were performed using the *lmer* function implemented in the *lme4* package [47] of R [48]. The *p*-values for fixed effects were computed using Satterthwaite's degrees of freedom method with the *lmerTest* package [49]. The schematic structures of the six linear models are summarized below with the dependent variable on the left side of the "~" symbol and the predictor variables on the right side:

Model 1: Number of pumps on *remaining* balloons that did not burst in the long-manipulation conditions ~ Luck, Balloon, Luck * Balloon

Model 2: Number of pumps on *remaining* balloons that did not burst in the long-manipulation conditions ~ Luck, Bin, Luck * Bin (*Bin with 4 levels*)

Model 3: Number of pumps on *remaining* balloons that did not burst in the short-manipulation conditions ~ Luck, Balloon, Luck * Balloon

Model 4: Number of pumps on *remaining* balloons that did not burst in the short-manipulation conditions ~ Luck, Bin, Luck * Bin (*Bin with 5 levels*)

Model 5: Number of pumps on *all* balloons that did not burst ~ Luck, Length, Balloon, Luck * Length, Luck * Balloon, Length * Balloon, Luck * Length * Balloon

Model 6: Number of pumps on *all* balloons that did not burst ~ Luck, Length, Bin, Luck * Length, Luck * Bin, Length * Bin, Luck * Length * Bin (*Bin with 6 levels*)

The factors *Luck* (lucky vs. unlucky), *Length* (long vs. short), *Balloon* or *Bin*, and their *two-way* and *three-way* interactions were entered as fixed effects into the models. The *Luck*, *Length*, and *Bin* factors were treated as categorical predictors and *Balloon* as a continuous predictor. Participants were modeled as random effects (random intercepts). As we used the treatment contrast, the reference level of a given factor served as the baseline to estimate the other levels. These were *lucky*, *long*, *Bin1* (Model 6), *Bin2* (Model 4), and *Bin3* (Model 2). The models were fit with restricted maximum likelihood parameter estimates (*REML*). Pairwise comparisons were performed by the *glht* function [50] (*p* values were adjusted with single-step method).

Tables

Table 1. Descriptive data of demographic variables and BART performance in Experiments 1–2 and in an explorative study presented in the Supplementary Material.

Experiment	Explorative study	Experiment 1				Experiment 2		
	–	Lucky long	Lucky short	Unlucky long	Unlucky short	Lucky	Unlucky	Baseline
Condition	–	*M*(SD)	*M*(*SD*)	*M*(*SD*)	*M*(*SD*)	*M*(*SD*)	*M*(*SD*)	*M*(*SD*)
n	156	20	20	20	20	30	30	30
Gender [Male/Female]	26/130	11/9	9/11	11/9	5/15	16/14	14/16	18/12
Age [years]	21.4 (3.9)	22.4 (1.6)	21.0 (1.1)	22.2 (1.3)	21.8 (1.3)	21.5 (1.6)	21.6 (1.6)	21.1 (1.4)
Education [years]	14.6 (2.1)	15.5 (1.3)	14.2 (0.9)	15.0 (1.1)	15.2 (0.9)	14.8 (1.4)	14.9 (1.4)	14.8 (1.6)
Mean adjusted pumps	8.3 (2.3)	8.7 (1.7)	9.3 (1.3)	5.7 (0.9)	6.5 (0.9)	8.1 (2.4)	7.1 (1.4)	7.9 (2.4)
Number of balloon bursts	12.4 (4.1)	11.3 (5.3)	14.2 (4.3)	10.1 (3.2)	9.8 (2.2)	12.1 (4.5)	9.5 (3.2)	11.0 (4.3)
Total score	711.7 (256.4)	797.2 (146.4)	758.6 (127.1)	405.1 (83.3)	517.0 (91.3)	651.1 (153.0)	624.0 (153.8)	644.6 (142.9)

Note. In Experiment 1, BART variables were calculated for the whole task (30 balloons), which included the initial phase with experimental manipulation (biased balloon characteristics). In Experiment 2, BART variables were calculated for the subsequent phase (30 unbiased balloons).

Table 2. Maximum number of successful pumps for each balloon in each condition in Experiments 1–2.

		Experiment 1				Experiment 2		
Bin	*Balloon*	Lucky long	Lucky short	Unlucky long	Unlucky short	Lucky	Unlucky	Baseline
Initial 1	*1*	No separate initial phase				**15**	**5**	**14**
	2					**15**	**5**	**8**
	3					**12**	**4**	**13**
	4					**12**	**4**	**8**
	5					**15**	**5**	**19**
Initial 2	*6*					**15**	**5**	**2**
	7					**15**	**5**	**5**
	8					**12**	**4**	**14**
	9					**15**	**5**	**19**
	10					**12**	**4**	**4**
1	*1*	**15**	**15**	**5**	**5**	7	7	7
	2	**15**	**15**	**5**	**5**	9	9	9
	3	**12**	**15**	**4**	**5**	2	2	2
	4	**12**	**15**	**4**	**5**	19	19	19
	5	**15**	**15**	**5**	**5**	5	5	5
2	*6*	**15**	8	**5**	8	4	4	4
	7	**15**	8	**5**	8	8	8	8
	8	**12**	12	**4**	12	5	5	5
	9	**15**	13	**5**	13	10	10	10
	10	**12**	5	**4**	5	8	8	8
3	*11*	8	9	8	9	18	18	18
	12	8	8	8	8	18	18	18
	13	12	11	12	11	3	3	3
	14	13	12	13	12	15	15	15
	15	5	12	5	12	7	7	7
4	*16*	9	6	9	6	9	9	9
	17	8	11	8	11	11	11	11
	18	11	11	11	11	18	18	18
	19	12	5	12	5	9	9	9
	20	12	4	12	4	19	19	19
5	*21*	6	9	6	9	7	7	7
	22	11	15	11	15	14	14	14
	23	11	7	11	7	13	13	13
	24	5	10	5	10	11	11	11
	25	4	6	4	6	14	14	14
6	*26*	9	12	9	12	13	13	13
	27	15	6	15	6	5	5	5
	28	7	8	7	8	4	4	4
	29	10	11	10	11	19	19	19
	30	6	7	6	7	5	5	5

Note. Values presented in the table were the same across participants. Initial phases during which we controlled for lucky, unlucky, or baseline experience are **boldfaced**. In Experiment 1, the initial phase was part of the main task including altogether 30 balloons; in Experiment 2, the initial phase included ten separate balloons that were followed by the subsequent phase with 30 balloons. Dashed horizontal lines denote separate time bins, each consisting of five consecutive balloons. Experiment 1 consisted of six bins; Experiment 2 consisted of altogether eight bins, two bins in the initial phase and six bins in the subsequent phase. Numbers in *italics* in the column labelled as “Bin” denote the sequential numbers of time bins; those in the column labelled as “Balloon” denote the sequential numbers of balloons. Maximum number of successful pumps means that if a participant inflated the given balloon one pump further, the balloon burst. Note that the remainder sequence of balloons was the same between lucky long and unlucky long conditions, and between lucky short and unlucky short conditions in Experiment 1. In addition, the first 20 balloons in the remainder sequence of all conditions were the same in Experiment 1. In Experiment 2, the subsequent phase was the same across all conditions.

Results

To ease meta-analytic work, Table 1 shows overall performance on the different versions of the BART presented in this paper measured by classical indices such as the mean adjusted number of pumps, the number of balloon bursts, and the total score that is the sum of reward (points) in the end of the task. In the results section below, the “number of pumps” or “pump number” refers to the number of pumps on balloons that did not burst. Only those effects are detailed from the balloon-wise and bin-wise analyses that are relevant regarding the hypotheses. The summary of all effects included in the linear mixed-effects models is presented in Supplementary Table S1. Since the treatment contrast provides inferential tests of simple effects and simple interactions (except for the highest-order effects), these terms are used below, if relevant.

Risk-taking behavior in the lucky long and unlucky long conditions (Model 1 & Model 2). After *long* initial manipulation had ended, unlucky experience yielded lower number of pumps on the remaining balloons than lucky experience (significant simple effect of *Luck*, β = -4.29, *SE* = 0.81, *t*(151.71) = -5.33, *p* < .001). However, as the task progressed, while the number of pumps increased on the remaining balloons in the unlucky long condition, it decreased in the lucky long condition (significant *Luck* * *Balloon* interaction, β = 0.12, *SE* = 0.03, *t*(468.51) = 4.00, *p* < .001; see Fig. 1a, c, e). More specifically, as compared with the first Bin after initial manipulation (i.e., Bin3), a significant decrease in the lucky long vs. unlucky long difference (*Luck* effect) was evidenced from Bin4 until the end of the task (all βs ≥ 1.89, *SE*s ≤ 0.51, *t*s ≥ 3.71, *p*s < .001, see Supplementary Table S1). A contrast matrix was set up that defined the comparison of *Luck* effect across the levels of *Bin*. Pairwise tests showed that the *Luck* effect did not change further across Bin4–Bin6 (│*z*s│ ≤ 1.46, *p*s ≥ .310).

Risk-taking behavior in the lucky short and unlucky short conditions (Model 3 & Model 4). After *short* initial manipulation had ended, unlucky experience yielded lower number of pumps on the remaining balloons than lucky experience (significant simple effect of *Luck*, β = -3.52, *SE* = 0.47, *t*(157.37) = -7.49, *p* < .001). Meanwhile, the number of pumps increased on the remaining balloons in the unlucky short condition and decreased in the lucky short condition (significant *Luck* * *Balloon* interaction, β = 0.08, *SE* = 0.02, *t*(557.14) = 3.98, *p* < .001; see Fig. 1b, d, e). Particularly, as compared with the first Bin after initial manipulation (i.e., Bin2), a significant decrease in the lucky short vs. unlucky short difference (*Luck* effect) appeared in Bin3 and was present until the end of the task (all βs ≥ 1.12, *SE*s ≤ 0.50, *t*s ≥ 2.75, *p*s ≤ .006, see Supplementary Table S1). Pairwise tests showed that this *Luck* effect did not change further across Bin3–Bin6 (│*z*s│ ≤ 1.73, *p*s ≥ .304).

Interim summary. Due to both long and short initial manipulations, the number of pumps was consistently lower in unlucky than in lucky conditions across the remaining balloons of the task. Meanwhile, this difference decreased in the second half of the task after experiencing approximately five unbiased balloons following initial manipulation. While participants in the unlucky condition increased pumping, those in the lucky condition slightly decreased this behavior in the remainder of the task, indicating the adjustment of behavior to recent experience. Although it seems that all participants adjusted their behavior in an opposite manner as a function of luck, it was not clear from these analyses whether the effect of long or short initial experience was more pronounced. This was tested below with Model 5 and Model 6.

Risk-taking behavior across all conditions and balloons (Model 5 & Model 6). When all conditions and balloons (manipulated and unbiased) were considered together, in line with the results above, consistently lower pump number in the unlucky than in the lucky condition was found (significant simple effect of *Luck*, $\beta = -5.46$, $SE = 0.45$, $t(149.45) = -12.01$, $p < .001$). The simple effect of *Length* was only significant in the bin-wise analysis, $\beta = 1.22$, $SE = 0.45$, $t(138.08) = 2.73$, $p = .007$, and not in the balloon-wise analysis, $\beta = 0.42$, $SE = 0.44$, $t(133.84) = 0.95$, $p = .345$. Accordingly, some slight indication was found for the number of pumps being higher in the short manipulation conditions than in the long ones.

As shown by the significant *Luck* * *Length* * *Balloon* interaction, $\beta = -0.05$, $SE = 0.02$, $t(1415.53) = -2.32$, $p = .020$, although the number of pumps increased in the unlucky condition and decreased in the lucky condition (significant simple interaction of *Luck* * *Balloon*), this change differed between the long and short conditions (see Fig. 1e). However, this significant three-way interaction indicated mostly the effectiveness of initial manipulation. A striking difference between lucky long and unlucky long conditions was observed in Bin1 and Bin2, where balloons were manipulated. Meanwhile, between the short conditions, this difference was only present in Bin1 and started to decrease in Bin2, where balloons became unbiased. Particularly, the lucky vs. unlucky difference was smaller in the short than in the long manipulation conditions in Bin2 and Bin3 than at the beginning of the task (Bin2: $\beta = 3.54$, $SE = 0.67$, $t(1396.93) = 5.28$, $p < .001$; Bin3: $\beta = 2.20$, $SE = 0.65$,

$t(1397.17) = 3.38$, $p < .001$). This was due to the steeply increasing number of pumps in the unlucky short condition right after the end of initial manipulation.

More importantly, during the second half of the task (Bin4, Bin5, and Bin6 as compared with Bin1), no difference appeared between the short and long conditions in how the lucky vs. unlucky difference changed as the task progressed (all ts ≤ 1.29, ps $\geq .197$, see Supplementary Table S1). Therefore, experiencing unlucky balloons either for longer or shorter duration yielded similar pump number after the integration of recent experience. Altogether, these modeling results with all experimental factors considered not only corroborated previous results (Model 1–4) but also revealed that behavior adjustment in the second half of the task was comparable between the length manipulation conditions.

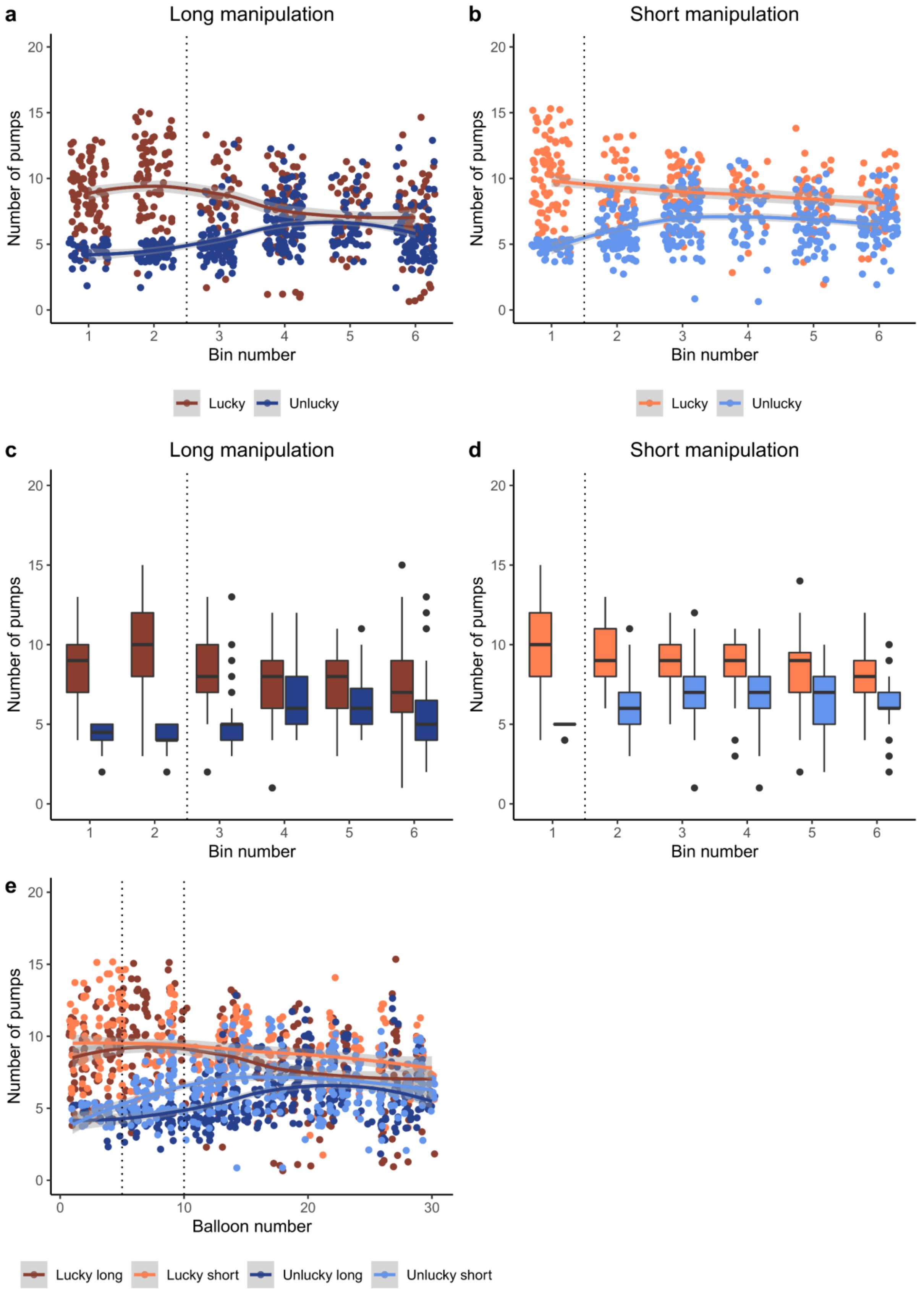

Figure 1. Results of Experiment 1. The numbers of pumps on balloons that did not burst are presented in each time bin in the long manipulation (a, c) and short manipulation (b, d) conditions, respectively. Vertical dotted

lines indicate that (lucky or unlucky) initial manipulation ended after the second (long manipulation) or the first (short manipulation) time bin. Each time bin consists of five consecutive balloons. Figure part (e) shows the numbers of pumps on balloons that did not burst across all conditions and balloons. Points denote individual data points in all figure parts. Shaded areas in figure parts (a, b, e) represent 95% confidence intervals for means, depicted with continuous lines.

Discussion

In Experiment 1, we showed that initial experience influenced subsequent risk-taking behavior. Unlucky compared with lucky initial experience led to overall lower risk taking. More importantly, approximately five balloons after the change in structure, all participants started to update their behavior: The number of pumps increased following unlucky experience, while it decreased following lucky experience in the remainder of the task. The pattern of change was comparable between long and short manipulation conditions. This is partially in contrast to our hypothesis that a persistent risk-averse behavior was expected after a long series of unlucky events (i.e., primacy effect). Namely, albeit unlucky participants converged to a more risk-averse behavior in both length manipulation conditions, behavior adjustment was still observed due to combining the outcomes of more recent balloon pumps with initial experience.

It is not sure in Experiment 1 that lucky and unlucky manipulation induced positive and negative experiences, respectively. At least, one cannot tell whether these experiences were more positive or more negative than a baseline experience. In addition, the number of balloons and their tolerance in the remaining phase of the task differed across conditions, which could have influenced how recent outcomes were evaluated and used in updating. The second experiment aimed to address these shortcomings of Experiment 1.

Experiment 2

In Experiment 2, we went beyond Experiment 1 in two aspects. First, we manipulated a separate initial phase with ten balloons that preceded a subsequent phase with 30 balloons. Second, in this initial phase, we used three conditions: baseline, lucky, and unlucky. This design enabled us to analyze risk-taking behavior on the exact same sequence of 30 balloons across all conditions in the subsequent phase. Moreover, with the use of the baseline condition, we could compare with a reference level whether individuals are more prone to take risks due to lucky experience and less prone to take risks due to unlucky experience.

Method

Participants. Ninety young adults took part in Experiment 2, 30 in each experimental condition (between-subjects design). None of them participated in Experiment 1. According to a similar power analysis as in relation to Experiment 1, the required total sample size would be at least 63 participants. Thus, our sample of 90 participants was sufficiently large to detect differences in the adjustment of risk-taking behavior across the conditions.

Participants were students from different universities in Budapest and young adult volunteers. All participants had normal or corrected-to-normal vision and none of them reported a history of any neurological and/or psychiatric condition. All of them provided written informed consent before enrollment. The experiment was approved by the United Ethical Review Committee for Research in Psychology (EPKEB) in Hungary and by the research ethics committee of Eötvös Loránd University, Budapest, Hungary; and it was conducted in accordance with the Declaration of Helsinki. As all participants were volunteers, they were not compensated for their participation. Descriptive characteristics of participants randomly assigned to the three different conditions are presented in Table 1.

Stimuli, design, and procedure. The appearance of the task was the same as in Experiment 1. Participants had to inflate altogether 40 balloons in this task. The first ten balloons belonged to the *initial phase*; the remaining 30 balloons belonged to the *subsequent phase*. Similar to Experiment 1, we chose specific values for the maximum number of successful pumps on each of the 40 balloons. The maximum pump values for each balloon in both phases, separately for each condition are presented in Table 2.

Regarding the initial phase, in the *lucky* condition, we used the same fixed series of values as in the lucky long condition of Experiment 1 (either 12 or 15 pumps). Similarly, in the *unlucky* condition, we used the same fixed series of values as in the unlucky long condition of Experiment 1 (either four or five pumps). For the *baseline* condition, we generated a random sequence of ten integers from a uniform distribution between two and 19, as balloon burst was enabled only after the third pump, and the maximum number of successful pumps was 19 in those versions that were used in our previous studies (e.g., [35]). Again, this series of baseline pump values was fixed and the same across participants. The mean of the maximum number of successful pumps – calculated for the initial phase – significantly differed across the three conditions, $F(2, 29) = 16.53$, $p < .005$. It was significantly lower in the unlucky than in the baseline and lucky conditions (unlucky: M = 4.60, SD = 0.52, baseline: M = 10.60, SD = 6.08, lucky: M = 13.80, SD = 1.55; unlucky vs. baseline: p = .001, unlucky vs. lucky: p < .001); but it was not significantly higher in the lucky than in the baseline condition (p = .059).

Regarding the 30 balloons of the subsequent phase, the fixed series of values were identical across the different conditions and across participants (see Table 2). These values were, again, generated from a uniform distribution between two and 19. The mean of the maximum number of successful pumps – calculated for the initial and the subsequent phases together (whole task) – did not differ significantly across the three conditions, $F(2, 119)$ =

2.00, p = .140 (unlucky: M = 8.88, SD = 5.26, baseline: M = 10.38, SD = 5.47, lucky: M = 11.18, SD = 4.92; unlucky vs. baseline: p = .201; lucky vs. baseline: p = .495; unlucky vs. lucky: p = .051). Hence, the manipulation of the initial phase did not considerably change the overall potential of risk taking.

Participants were told that they were going to have ten balloon trials in the initial phase of the task and then 30 balloon trials in the subsequent phase. The starting score was zero in both phases, about which participants were also informed. Importantly, no information was provided about the change in the payoff structure.

Data analyses. We followed the same approach as in Experiment 1. We performed linear mixed-effects analyses on the number of pumps on each balloon that did not burst as the dependent variable. Again, each balloon was assigned to a five-balloon-long time bin of the task. First, to check the effectiveness of initial manipulation, two models (balloon-wise and bin-wise) were fit to the data of the initial phase. Second, to evaluate the effect of initial experience on subsequent risk-taking behavior, two models were fit to the data of the subsequent phase.

The initial phase consisted of ten balloons or two bins; the subsequent phase consisted of 30 balloons or six bins. The factors *Condition* (baseline, lucky, unlucky), *Balloon* or *Bin*, and their *two-way interactions* were entered as fixed effects into the models. The *Condition* and *Bin* factors were treated as categorical predictors and *Balloon* as a continuous predictor. Participants were modeled as random effects (random intercepts). With the treatment contrast, the reference level of a given factor (i.e., *baseline*, *Bin1*) was used to estimate the other levels. The four linear models are summarized below with the dependent variable on the left side of the "~" symbol and the predictor variables on the right side:

Model 1: Number of pumps on balloons that did not burst in the *initial phase* ~ Condition, Balloon, Condition * Balloon

Model 2: Number of pumps on balloons that did not burst in the *initial phase* ~ Condition, Bin, Condition * Bin (*Bin with 2 levels*)

Model 3: Number of pumps on balloons that did not burst in the *subsequent phase* ~ Condition, Balloon, Condition * Balloon

Model 4: Number of pumps on balloons that did not burst in the *subsequent phase* ~ Condition, Bin, Condition * Bin (*Bin with 6 levels*)

Results

The "number of pumps" or "pump number" below refers to the number of pumps on balloons that did not burst. Only those effects are detailed from the balloon-wise and bin-wise analyses that are relevant regarding the hypotheses. The summary of all effects included in the linear mixed-effects models is presented in Supplementary Table S2.

Risk-taking behavior in the initial task phase (Model 1 & Model 2). Unlucky initial experience yielded significantly lower pump number on balloons of the *initial phase* than baseline experience (β = -1.96, *SE* = 0.53, *t*(169.20) = -3.67, *p* < .001). Lucky initial experience yielded significantly higher pump number than baseline experience only in the bin-wise model, β = 1.01, *SE* = 0.46, *t*(96.90) = 2.19, *p* = .031, and not in the balloon-wise one. However, participants in the lucky condition showed increased pump number relative to the baseline condition with later balloons, especially in Bin2 (significant *Condition * Balloon* and *Condition * Bin* interaction, β = 3.25, *SE* = 0.34, *t*(523.45) = 9.50, *p* < .001, see also Supplementary Table S2 and Fig. 2c, e). Overall, initial manipulation seemed to be effective, as lucky and unlucky conditions differed from the baseline in the expected directions.

Risk-taking behavior in the subsequent task phase (Model 3 & Model 4). Unlucky initial experience yielded significantly lower pump number on balloons of the *subsequent* *phase* than baseline experience (β = -1.48, *SE* = 0.55, $t(102.5) = -2.70$, $p = .008$). Meanwhile, the effect of lucky experience did not reliably differ from that of the baseline experience during the subsequent phase (β = 0.08, *SE* = 0.56, $t(108.9) = 0.14$, $p = .889$). Participants in all conditions increased pumping as the task progressed (simple effect of *Balloon*, β = 0.11, *SE* = 0.01, $t(1621) = 12.01$, $p < .001$; see Fig. 2a, b). As compared with Bin1, this increase was significant from Bin3 until the end of the task (all βs $\geq$ 0.57, *SE*s $\leq$ 0.30, *t*s $\geq$ 2.14, *p*s $\leq$ .033). Though, further change was not observed in the second half of the task, except between Bin4 and Bin5 ($z = 2.81$, $p = .044$; Bin4 vs. Bin6: $z = 1.49$, $p = .628$, Bin5 vs. Bin6: $z = -0.80$, $p = .959$).

The increasing pump number with further balloons differed between the unlucky and baseline conditions, β = 0.06, *SE* = 0.01, $t(1621) = 4.55$, $p < .001$, but it did not between lucky and baseline conditions, β = 0.01, *SE* = 0.01, $t(1621) = 0.60$, $p = .549$. This *Condition* * *Balloon* interaction was corroborated by the bin-wise analysis, indicating significantly increased pump numbers in the unlucky condition in all time bins relative to Bin1 (all βs $\geq$ 0.76, *SE*s $\leq$ 0.41, *t*s $\geq$ 2.14, *p*s $\leq$ .032; see Fig. 2b, d, f). At the same time, pairwise tests showed that across the levels of *Bin*, this relative increase in the unlucky condition did not change further ($|zs| \leq 2.79$, *p*s $\geq$ .063). Relative to Bin1, the unlucky vs. baseline difference was larger than the lucky vs. baseline difference in Bin2, Bin5, and Bin6, indicating a steeper increase in the unlucky than in the baseline or lucky conditions (*z*s $\geq$ 3.20, *p*s $\leq$ .017).

Overall, after completing approximately ten balloons of the subsequent phase, participants started to increase their pumping behavior that became consistent in the second half of the task. While this increase was similar in the baseline and lucky conditions, it was steeper in the unlucky conditions, as those participants showed lower pump number in the first half of the task because of initial manipulation.

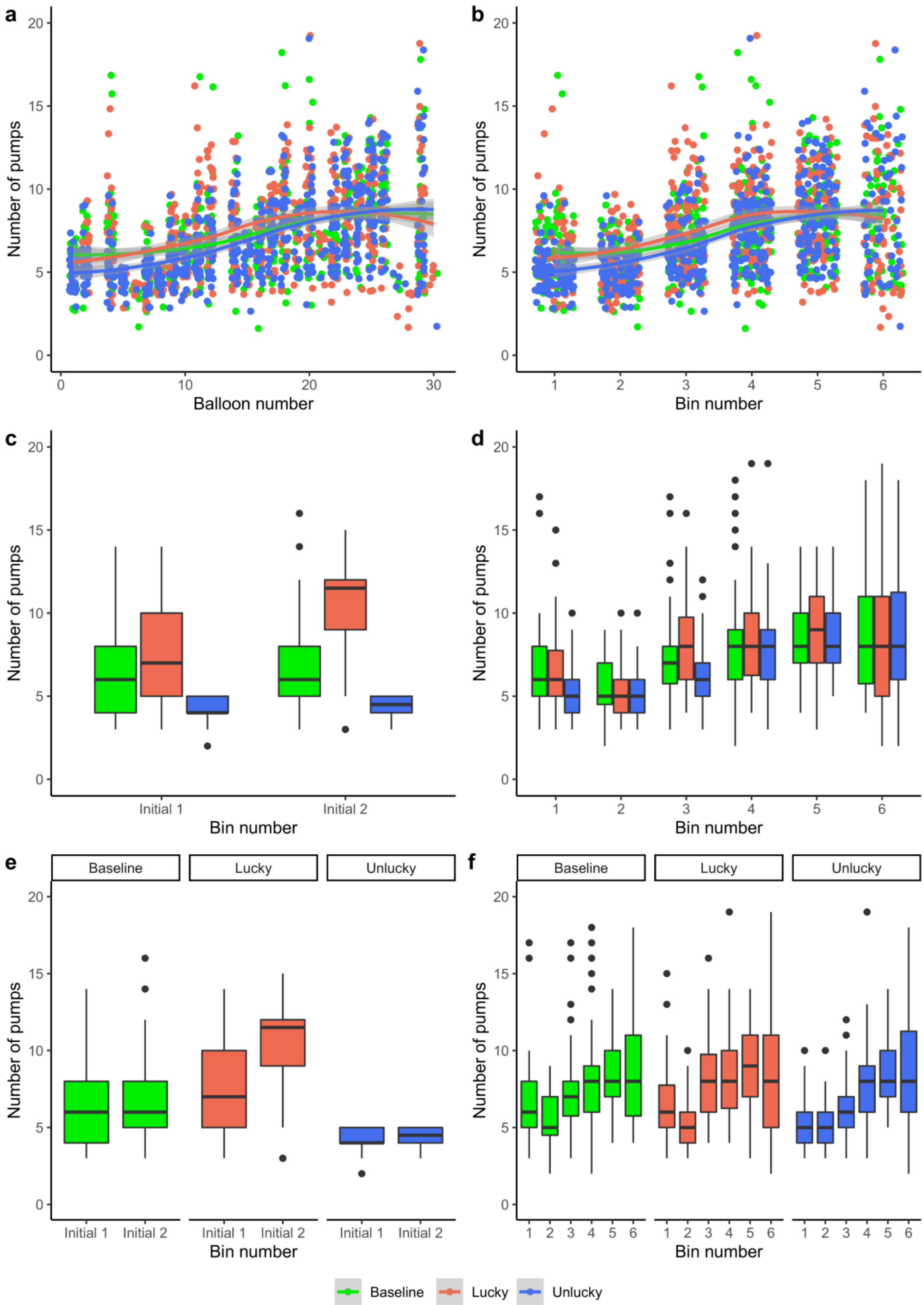

Figure 2. Results of Experiment 2. The numbers of pumps on balloons that did not burst are presented across all conditions (baseline, lucky, unlucky) and balloons as well as in each time bin of the subsequent phase in

figure parts (a, b), repectively. Each time bin consists of five consecutive balloons. Separate figure parts show the initial (c, e) and subsequent (d, f) phases of the task, each containing two and six time bins, respectively. These phases were separated by a short pause lasting for a few seconds. While figure parts (c, d) show the number of pumps compared across the conditions, figure parts (e, f) show the number of pumps separately for each condition. Points denote individual data points in all figure parts. Shaded areas in figure parts (a, c) represent 95% confidence intervals for means, depicted with continuous lines.

Discussion

Experiment 2 involved not only lucky and unlucky conditions but also a baseline condition; and the initial phase with experimental manipulation was separated from the subsequent phase where the adjustment of risk-taking behavior was measured. Although we expected to find a primacy effect with a later shift in risk-taking behavior opposite to the direction oriented by initial experience such as in Experiment 1, partially different results were revealed. All participants gradually increased their risk taking in the subsequent phase due to adaptation to the changed structure, irrespective of the valence of initial experience. As participants in the unlucky condition started the subsequent phase with lower pump number due to initially negative experiences, they increased pumping more than other participants. The modulating effect of initial experience across conditions was no longer observed in the second half of the task, as the number of pumps became similar. We also expected that the overall effect of negative experience would be more distinct from baseline than the effect of positive experience, which was confirmed by these results. However, the behavioral pattern of the lucky condition was comparable to that of the baseline condition in the subsequent phase. Still, some indication was found in the initial phase that positive experience yielded higher risk taking than baseline experience.

General Discussion

Summary of findings

This study examined how initial experience with outcome probabilities influenced later risk-taking behavior in an experience-based risky decision-making task. To this end, we inserted an unsignaled and unexpected change point in the payoff structure of the BART, before and after which outcome probabilities considerably differed. The change point occurred after one-sixth or one-third of trials in the first experiment, and between the initial and subsequent phases in the second experiment. Importantly, the task structure after the change point was unbiased and comparable across experimental conditions, only the relative valence of events differed as a function of previous experience. Several results contradicted our original hypotheses. Particularly, both experiments suggested that participants in all conditions adjusted their risk-taking behavior to the changed payoff structure of the task; however, the impact of initial experience was simultaneously observed, especially in the first experiment.

Results of the first experiment showed that initially experiencing negative events led to consistently decreased risk-taking behavior. However, even if initial experience indicated that more cautious behavior was advantageous, risk taking increased after the change in structure. Similarly, if initial experience indicated that high risk could be taken, risk taking decreased after the change. The length of initial experience did not reliably influence the pattern of behavioral change. Results of the second experiment further highlighted that the impact of initial negative experience could be overcome by integrating recent experiences. In all conditions, participants gradually increased their risk taking as the task progressed. Risk-taking behavior after positive initial experience was adjusted to an extent to match behavior after baseline initial experience. This was not the case after negative initial experience: Risk taking remained lower than after baseline initial experience, but it was also adjusted yielding similar behavior across the conditions later in the task.

Adjustment of risk-taking behavior in the BART

It is a common approach when analyzing BART data to track how participants increase the number of pumps as they continuously integrate experiences across the balloon trials [21,32,46,51-53]. Although behavior change was observed in both of our experiments, this was not necessarily an increase in pump number. Only participants of the unlucky conditions increased pumping in the first experiment. Meanwhile, in the second experiment, pumping behavior gradually increased in all conditions. This also meant that while lucky experience led to more cautious behavior after the end of manipulation in the first experiment, the opposite was observed in the second experiment.

These between-experiments differences could be explained by the different balloon tolerances in the remaining and subsequent phases of each experiment. Particularly, in the second experiment, mean balloon tolerances were relatively high in Bin3, Bin4, and Bin5. Accordingly, balloon pumps were increased, and the frequency of balloon bursts was decreased in these time bins (Table 2 and Supplementary Fig. S3). Meanwhile, in the first experiment, mean balloon tolerances in the middle of the task were lower than in the second experiment; and, more importantly, these values were lower than over the initial balloons of the lucky long condition (Table 2 and Supplementary Fig. S2). It is possible that participants reacted in a more sensitive manner to changes in the underlying structure when the manipulated phase was part of the main task; therefore, they did not pump the balloon to a larger size as the task progressed in the first experiment. The short pause between the two phases of the second experiment might have served as a signal indicating an unspecific change. Thus, after some (probably surprising) experience in the early trials of the subsequent phase, participants might have perceived this phase as a separate task and increased pump number as usually observed in the original BART but see [31].

Irrespective of length manipulation, results of the first experiment are mostly in line with the findings of Koscielniak, et al. [23] and Bonini, et al. [24], indicating not only primacy but also recency effects in the BART. In contrast, the study of Yau, et al. [41] did not find evidence for change in risk taking when the original BART was followed by a rigged BART with 50% probability of balloon burst. In that study, however, an automatic response version of the BART [54] was used, which lacks the experience of a dynamic inflation process and decisions might be more explicitly verbalized. Our study indicates that if participants are free to test the task structure and no explicit information is provided that might constrain this behavior (cf. [26]), they continuously adapt to the changing structure. As shown by the between-experiments differences, this adaptation is determined by the structure per se: If reduced risk taking became optimal, individuals would quickly update how they react to further balloons.

In the second experiment, behavior change was similar between the lucky and baseline conditions and it differed from the unlucky condition. This might indicate that the processing of negative events in the unlucky condition differently influenced later risk-taking behavior as compared with the other conditions. This asymmetry was expected since stronger effect of negative manipulation has already been found in previous BART-studies [24-26]. However, we could propose only cautious explanations for this finding. First, individuals in the unlucky condition might have compensated more for losses experienced in the initial phase than those in the other conditions (cf. [24]). This explanation is loosely related to the notion of loss aversion or the asymmetric sensitivity to gains and losses (cf. [55]). Second, altered sensitivity to negative events might have contributed to the observed behavioral difference, but this should be directly tested in neuroimaging or neurophysiological studies (cf. [25,37,56]). Third, it is probable that methodological issues played a role. While the maximum number of successful pumps was not significantly higher in the lucky than in the baseline condition in the initial phase, it was much lower in the unlucky condition (see Stimuli, design, and procedure section). Therefore, initial experience could have been similar between lucky and baseline conditions, yielding comparable risk-taking behavior later in the task.

The putative cognitive underpinnings of the observed choice behavior

Although we cannot be sure that participants explicitly estimated risk when performing the BART, we assume that beliefs (expectations) have been formed about the action-outcome contingencies (cf. [4,5]). A previous study revealed that experiencing initial bad luck in the BART was associated with higher reward sensitivity, higher initial belief that the balloon will explode, and more uncertainty about this belief [57,58]. Neurophysiological results also suggest that individuals form internal models of the decision environment while performing the BART [25,35,36]. Accordingly, based on their initial beliefs, participants experiencing early negative events in the BART could have expected more balloon bursts or volatile outcome probabilities later in the task, yielding more risk-averse behavior [4,5].

One might attempt to explain our results in terms of the general anchor-and-adjustment model of belief updating [1]. However, mapping the structure of the BART onto tasks and concepts that the model has been based on is not obvious. In this model, the encoding of evidence (evaluation or estimation), the processing of evidence (step-by-step revisions or the adjustment of the initial anchor based on a series of evidence), and the sensitivity to evidence are critical subprocesses. The combination of these subprocesses together with task characteristics (complexity, length of sampling) determine how the order of information could possibly influence decisions.

In the BART, the mode of encoding could have been estimation, i.e., the sequential integration of information across time. At the same time, whether the given balloon burst or increased after a specific number of pumps could have been evaluated merely as positive or negative deflection from previous experience. Therefore, participants could have used both the evaluation and estimation modes of encoding. In addition, other unknown heuristics might have played a role, as well. The history of previous balloon pumps and balloon tolerances could be considered as a long series of complex evidence not only in the long manipulation condition but also in the other ones. Both the processing of evidence and the response mode involves step-by-step operations since risky decisions are made at each step of the balloon inflation process. Although the length and complexity of the task favors this process, it is possible that the end-of-sequence process was also used or a switching between the strategies might have occurred: Collecting the accumulated reward could have been based on the aggregated experience with a series of successful balloon pumps and with the expectation of a near balloon burst [36]. The attitudes toward negative and positive evidence might be constrained by the initial bias: Those who experienced mostly negative (or positive) events during the initial phase might have remained highly sensitive to negative (or positive) evidence, but it is also possible the other way around [57].

Thus, the BART in the present form involves a long series of uncertain decisions and puts high processing effort on those individuals who might try to explicitly learn the task structure. Considering all processes, the prediction of the anchor-and-adjustment model would be a force toward primacy effect. (However, the model does not specify whether different order effects would be observed if evidence is simple or complex in long series.) Although primacy effect was found in both experiments, recent experience also guided the update of choice behavior, which was not constrained to short initial experience (cf. Table 2 in [1]). Therefore, the observed findings might not be wholly interpreted along this theoretical model.

Relatedly, one of our central questions is whether the length of manipulation influences the update of initial beliefs. Indeed, we found overall higher number of pumps with short than long manipulation in the bin-wise model but not in the balloon-wise model. The number of pumps decreased in an apparently milder manner after the lucky short than after the lucky long manipulation. However, our conservative conclusion would be that the different lengths of positive or negative experience would not considerably alter behavior adjustment after manipulation. In our experiments, participants saw only the accumulated total score and the score collected from the previous balloon on the screen; therefore, no detailed statistics were available about balloon tolerances. Thus, it is conceivable that participants in all conditions did not explicitly track and memorize past events. Instead, they changed their strategy in a dynamic and implicit manner, according to experiences on the latest balloons. The weaker memory traces of the initial payoff structure might have contributed to quick adaptation in general, irrespective of the length and valence of early experience (cf. [13]). The second experiment also indicated the relatively week integration of early memory traces on action-outcome contingencies, as initial manipulation did not considerably alter subsequent risk-taking behavior. Although the role of multiple memory processes has been emphasized in value-based decision making in predicting the likely outcomes of decisions for a review, see [31,59], this notion seems to be relevant only to belief updating later in the task.

Either reflecting memory constraints or not, it has been proposed that individuals tend to underweight the probability of rare events when making decisions from experience. Accumulating evidence implies that this tendency originates from relying on relatively small samples and overweighting recent experiences [2,7,29]. Participants in the unlucky conditions sampled the balloons less than those in the lucky conditions, even after the end of manipulation (i.e., lower pump number on balloons that did not burst). Thus, they less likely encountered balloons with very high tolerances, which might have contributed to underestimating the variance of balloon tolerances (i.e., the probability of rare events). Simultaneously, they recently and frequently encountered balloons with “medium” tolerances that were *larger* than those during initial unlucky manipulation. In turn, these frequent events could have been overweighted yielding an increase in risk-taking behavior. Participants in the lucky conditions with more sampling encountered higher variance of balloon tolerances, which might have eventually yielded more risk-averse behavior [5]. Similar mechanisms could have contributed to the results of the second experiment, at least in the case of the unlucky condition. However, this theoretical account could not necessarily explain choice behavior of participants in the lucky and baseline conditions in the second experiment, as they sampled the balloons to a larger extent. In their case, local sampling biases could have introduced dynamic changes in risk sensitivity, yielding increased risk taking in time [6]. Regarding this perspective, we suggest that processing biases are present and could be adaptive in dynamic environments if the goal is to maximized reward.

Along this line, the results can be interpreted according to the principles of reinforcement learning. It is possible that a shift from goal-directed to habitual behavior occurred, guided by model-based followed by model-free processes [60,61]. Individuals might have performed the task according to internal models based on initial experiences about action-outcome contingencies. By integrating recent experiences, these initial internal models might have gradually changed. During the early phase of task solving with less experience, choices based on a model-based process might be more reliable, since its short-term predictions could be more accurate than long-term predictions of a model-free process. With more experience, the model-based process might become less reliable, since initial internal models could contain inaccuracies that are denoted by unexpected feedback events [60,61]. As experience accumulates, a shift is expected from a model-based to a model-free process. The choice behavior found in the first experiment likely reflects such a shift between these processes. This is not that clear in the second experiment, maybe due to weaker (initial) internal models.

Taken together, the interpretations of the observed effects remain tentative in terms of the potential cognitive processes. Experimental designs that not only involve the currently investigated factors but also directly manipulate the critical factors of the related theoretical perspectives are necessary. In this respect, computational models that account for the effect of initial experience might be considered: With such analyses, initial experience per se could be quantified and other parameters of the task could be compared across participants and groups/conditions while controlling for this effect [43,45,57,62].

Methodological considerations

Many studies using the BART and examining influential factors of risk taking (e.g., the effect of reward type, gender, age, situational factors, and clinical symptoms, see [32,34,36,63,64]) could have involved the effect of initial experience in an uncontrolled manner. As the results of our explorative study presented in the Supplementary Material indicate, even when initial experience is not directly manipulated, individuals would pump the balloons larger during the task if they experienced more successful pumps before balloon bursts within the first five trials (see also Supplementary Fig. S1). Thus, the impact of initial experience possibly varies across individuals and might involuntarily contribute to the experimental effects and group differences that have been the main questions of a given study. Overall, it seems that initial experience should be considered when using the BART.

Limitations

Although our findings indicated the continuous adjustment of behavior in all conditions, the design of the experiments inherently limited what participants could initially learn about the balloons. Participants' baseline belief about the pump number that balloons could have tolerated was not fixed a priori before the manipulation. They might have established this belief based on the experiences gathered during the first few trials (cf. [6,65]). However, it was limited to what size they could pump the balloons at the beginning of the task; and it was also unknown to what degree they were prone to pump these balloons.

Relatedly, an inherent limitation of the BART is that it provides one-sided censored data, since burst events terminate trials perforce. Therefore, burst trials cannot reveal to what extent participants were willing to take risks or what were the underlying processes that determined the pump number on those trials (e.g., risk taking, impulsivity, task engagement or motivation, and reduced sensitivity to negative feedback). Moreover, by excluding these trials, the reliability of data could slightly decrease (i.e., fewer trials), and this remaining data would still include any effects that the burst events had on subsequent trials [43].

In contrast to previous studies showing the profound effect of luck on later risk taking [30,66-68], we did not investigate individual differences in beliefs about luck, and we did not ask in what degree participants felt themselves lucky after the entire task or after the initial phase. Similarly, we did not require participants to track and rate the confidence they had in their choice. We deliberately changed the underlying structure in an unsignaled and unexpected manner, which did not allow explicit questions about the sense of luck and/or luck beliefs.

Participants received neither compensation for participation nor bonus based on task performance because of practical reasons. This might be an important limitation of this study. Recent work has implied that not only the behavioral indices but also the neurophysiological correlates of negative feedback processing are enhanced if real money instead of hypothetical reward is used in the BART [64,69]. Nevertheless, according to the impressions of the experimenters during debriefing, participants were still motivated to perform the task as if gains and losses were real.

Conclusions

This study confirmed that the combination of both primacy and recency effects contributes to experience-based risky decision making. Moreover, the study has new theoretical contribution by revealing that extended early experience does not induce more profound primacy effect than brief early experience. Instead, choice behavior is adjusted by integrating recent experiences of outcome probabilities into the internal models of the decision environment. Therefore, while choice behavior remains risk averse after early negative events, this attenuates with the accumulation of new experiences. Relatedly, the present study also found that negative events have a more influential role in shaping choice behavior. Several factors could underlie the observed effects, such as weak memory traces on initial outcome probabilities, the overweighting of recent experiences, and a shift from goal-directed to habitual behavior; all of which necessitate further investigation. In sum, by showing that initial beliefs are updated to promote adaptation, the present results extend the understanding of risky decision making in volatile environments.

Data availability

All data and analyses codes to reproduce the results are available in the following online repository: https://osf.io/bwzfa/?view_only=f0920ce7759144ceb4be81318cc76f75

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Author contributions

A. K. designed the study, created the scripts running the experiments, analyzed data, and wrote the manuscript; Z. K. designed the study, analyzed data, contributed to the interpretation of the results, wrote the manuscript, and critically revised previous versions of the manuscript; Á. T. designed the study, supervised data acquisition, analyzed data, wrote the manuscript, and critically revised previous versions of the manuscript; N. É. designed the study, analyzed data of the explorative study presented in the Supplementary Material, contributed to the interpretation of the results, and critically revised previous versions of the manuscript; K. J. designed the study and critically revised previous versions of the manuscript, E. T-F. analyzed data and revised previous versions of the manuscript; V. Cs.

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Competing interests

The authors declare no competing interests.