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RESEARCH ARTICLE

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The Zero Effect: An Eye-Tracking Study of Affect and Motivation in Risky Choices

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ABSTRACT

Decision makers often prefer safe wins over risky gambles, even if the latter promise higher payoffs than the former. One mechanism that explains this choice pattern is the certainty effect, whereby probabilities of 0 and 1 are interpreted accurately but intermediate probabilities are distorted by diminishing sensitivity. We tested an alternative explanation that was recently proposed, the idea that people would be motivated by avoiding zero outcomes rather than being attracted to sure gains. This zero-outcome aversion in gain-domain choices was called the zero effect. By analogy, we proposed that decision makers would approach zero outcomes in the loss domain. Two eye-tracking experiments investigated visual attention as a key component of the zero effect in the gain domain (Experiment 1) and the loss domain (Experiment 2). Choices were consistent with the zero effect. In the gain domain, gambles were chosen less frequently if they included a zero outcome. In contrast, zero-outcome gambles were chosen more frequently in the loss domain. Eye movements and pupillometry indicated that zero outcomes in both domains (a) were less frequently fixated than other outcomes and (b) were associated with increased arousal. We concluded that domain-specific affective responses to zero outcomes aligned with approach/avoidance motivation. These distinct motivations in turn biased information search and choice behavior.

1 | Introduction

Research on prospect theory (Kahneman and Tversky 1979; Tversky and Kahneman 1992) suggested for choices between simple gambles that probabilities of 0 and 1 were perceived accurately, as opposed to intermediate probabilities that were distorted by diminishing sensitivity to probabilities. Specifically, people underestimated medium and large probabilities and opted for sure gains whenever available. The pattern persisted even when the expected value of the chosen option was smaller than that of a risky alternative. This suboptimal choice

regularity is also known as the certainty effect (Kahneman and Tversky 1979; Wakker 2010; see also Ruggeri et al. 2020). Accordingly, zero-variance lotteries that promise a sure gain exert a special appeal on decision makers.

Incekara-Hafalir, Kim, and Stecher (2021) challenged the certainty-effect explanation of preferences for sure gains. They argued that aversion to zero outcomes, rather than the appeal of sure gains, drove choices between simple gambles. To examine the zero effect in risky choices (i.e., zero-outcome aversion), we conducted two eye-tracking experiments to investigate affect

Supplementary materials and data for this article are stored on the Open Science Framework (see <https://osf.io/rzd8c>). A report of Experiment 1 was previously published as part of a doctoral dissertation (Ludwig 2020).

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and motivation in gambles with and without zero outcomes across the gain and the loss domain. Our aim was to explore visual attention as a potential key component of the decision processes driving the zero effect and the certainty effect.

Zero outcomes are of interest in otherwise completely gain-oriented or loss-oriented decision environments. We argue that zero outcomes elicit distinct affective responses associated with avoidance/approach motivation in gain/loss frames. These processes might translate into attentional and behavioral biases that become observable in eye movements, pupillary responses, and lottery choices. In the next sections, we first review evidence for the certainty effect and the zero effect in risky choices. We then turn to research on attentional processes in decisions under risk generally and to selective attention to specific gamble features in particular. Section 4 explains our hypotheses in detail.

2 | Preferences for Sure Gains and Aversion of Zero Outcomes

The common ratio effect (Allais 1953) describes a striking violation of expected utility theory. Consider the choice between a sure gain of \$3000 and a gamble with 80% chance to gain \$4000 or nothing otherwise. Typically, a clear majority of decision makers prefers the sure gain even though the expected value is higher for the gamble. For instance, Kahneman and Tversky (1979) reported that 84.2% opted for the sure gain, consistent with a certainty effect in risky choices.

Consider a second lottery, with one gamble with 25% chance of gaining \$3000, or else nothing, and an alternative gamble with 20% chance of gaining \$4000, otherwise nothing. This choice is different from the first one only in that its probabilities are scaled down by a common factor of 0.25. Expected utility theory implies that decision makers who preferred the sure option in the first decision task should also opt for the safer gamble in the second one. Kahneman and Tversky (1979) reported that 68.4% of decision makers chose the risky option, revealing a striking preference reversal when scaling down gambles by a common factor.

This pattern was replicated numerous times (Ballinger and Wilcox 1997; Barron and Erev 2003; Baucells and Heukamp 2010; Loomes and Sugden 1998) and remained robust for risky choices (but see Blavatskyy, Ortmann, and Panchenko 2021; Blavatskyy, Panchenko, and Ortmann 2023, arguing that it is rather fragile). Yet, the common ratio effect can be reversed under certain conditions (Blavatskyy 2010) and is susceptible to framing effects (Harless 1992; Harman and Gonzalez 2015) and the decision domain (M. Schneider and Shor 2017). In this article, we focus exclusively on common ratio lotteries, not further considering common consequence lotteries.

The conventional explanation for the common ratio effect is that probabilities differ in their impact on the valuation of prospects. In cumulative prospect theory (CPT), this idea was formalized as the probability sensitivity parameter (Kahneman and Tversky 1979; Tversky and Kahneman 1992). It captures diminishing sensitivity to probabilities with increased distance to certainty, that is, people are more sensitive to changes in probabilities near 0 and 1 than

they are to changes of intermediate probabilities. This provides an explanation for the common ratio effect, and the certainty effect, elucidating why decision makers generally prefer sure gains over risky gambles, even if the former have lower expected value.

Incekara-Hafalir, Kim, and Stecher's (2021) experiment suggested that decision makers in common consequence problems might be primarily motivated to avoid zero outcomes. Avoidance motivation alone accounted for the observed violations of expected utility theory.

In principle, sure gains appear particularly attractive because they occur with certainty. Choosing a safe, zero-variance outcome over a risky gamble minimizes the decision risk. Assuming that decision makers generally are risk averse (e.g., Holt and Laury 2002) and that probabilities are not represented linearly in risky choices (Kahneman and Tversky 1979), preference for sure gains seems natural. But when a sure gain is pitted against a zero outcome, decision makers might opt for the sure gain simply because they are motivated to avoid the zero outcome, rather than being attracted by certainty.

Indeed, many studies, including seminal work by Kahneman and Tversky (1979), contrasted sure gains with an option that included the risk of ending up empty-handed. This lottery choice setup could not disentangle the certainty effect and the zero effect. The certainty effect could be confounded with zero-outcome aversion, because zero outcomes were typically presented jointly with a sure gain in the alternative option.

Incekara-Hafalir, Kim, and Stecher (2021) presented evidence for the idea that, in the gain domain, zero-outcome avoidance rather than the appeal of certainty was a compelling explanation for expected utility violations. Evidence for the certainty effect was “weak to nonexistent” (Incekara-Hafalir, Kim, and Stecher 2021, 751). These findings aligned well with another crucial feature of CPT, the assumption that “losses loom larger than gains” (Kahneman and Tversky 1979, 279). This claim holds that decision makers generally seek to avoid losses and they do so more strongly than approaching equivalent gains (Tversky and Kahneman 1992).

It appears plausible from an aspiration-level perspective (Lopes and Oden 1999; Payne, Laughunn, and Crum 1980) that decision makers reject zero outcomes in the gain domain if their reference point for a satisfactory outcome is above zero. To the extent that other outcomes are above the aspiration level, decision makers might experience a zero outcome as a loss. Therefore, they might anticipate frustration, perhaps because they were hoping to win at least some money.

In the loss domain, zero outcomes are very attractive options one might pick because the alternatives result in a lower payoff. If an aspiration level is below zero, zero outcomes are the only option to prevent losses. Zero outcomes may thus represent satisfactory outcomes that exceed the aspiration level. In the loss domain, zero outcomes should therefore be linked to approach motivation.

Regret theory (Bleichrodt and Wakker 2015; Loomes and Sugden 1982) suggests that the affective experience of receiving

a given outcome depends not only on the utility of that outcome but also on the utility of alternative outcomes. Decision makers may experience regret if the consequences of their choice are less desirable than alternative outcomes. Decision makers may also anticipate regret, as they know that picking one option entails dispensing other desirable alternatives. Sometimes, decision makers try to reduce the chances of experiencing post-decisional regret (see, e.g., Mojzisch, Häusser, and Leder 2020; Zeelenberg 1999).

Work on the “ostrich effect” in behavioral finance relates to this idea. Karlsson, Loewenstein, and Seppi (2009) (see also Galai and Sade 2006) observed that pre-decisional information acquisition was driven by the information’s hedonic quality and that allocating attention to information intensifies this information’s impact on decisions. Similarly, investors monitored their portfolios more actively in rising markets but, like the ostrich, “put their heads in the sand” and avoided additional information when markets were flat or falling (Karlsson, Loewenstein, and Seppi 2009). If decision makers faced with risky choices seek to reduce the (anticipated or experienced) negative affect elicited by zero outcomes, they would not gather further information on zero outcomes by paying more attention to these outcomes than to others. Conversely, in the loss domain, decision makers may anticipate rejoicing when picking zero-outcome options (Loomes and Sugden 1982). That is, decision makers experience joy if it turns out that they choose the best option given the circumstances. Anticipated rejoicing in the loss domain may bias attention and choices toward zero outcomes in turn.

3 | Visual Attention in Risky Choices

Researchers increasingly rely on the measurement of eye movements and pupillometry to investigate the attentional processes involved in economic decisions (Alós-Ferrer, Jaudas, and Ritschel 2021a, 2021b; Fiedler and Glöckner 2012; Krajbich, Armel, and Rangel 2010; Lohse and Johnson 1996; Orquin and Mueller Loose 2013; Schulte-Mecklenbeck, Kühberger, and Johnson 2019; Smith and Krajbich 2019; Stewart, Hermens, and Matthews 2016). Eye-tracking is useful to explore automatic visual attention processes in decision making because it captures unconscious processes. Growing evidence suggests that visual attention is closely tied to value-based choices. For instance, people fixate the option they eventually choose longer and more frequently than other options (Smith and Krajbich 2019; see also Bordalo, Gennaioli, and Shleifer 2012; Callaway, Rangel, and Griffiths 2021; Ludwig, Jaudas, and Achtziger 2020).

Earlier research demonstrated that zero outcomes typically received comparatively less attention than other gamble attributes (Brandstätter and Körner 2014; Franco-Watkins and Johnson 2011; Glöckner and Herbold 2011; Pachur et al. 2018; Schulte-Mecklenbeck et al. 2017). Pachur et al. (2018, see their Appendix) found that information on zero outcomes and their probabilities was substantially less frequently acquired than information on any other gamble attribute in a MouselabWEB experiment. This observation was in line with previous eye-tracking studies (Brandstätter and Körner 2014; Franco-Watkins and Johnson 2011; Glöckner and Herbold 2011).

Schulte-Mecklenbeck et al. (2017) used a lottery choice task that included lotteries with zero outcomes. On average, gamble outcomes were attended to more often than probabilities. Minimum outcomes (in some lotteries, zero outcomes) were less frequently viewed than maximum outcomes. Schulte-Mecklenbeck et al. (2017, 1008) pointed out that “in terms of calculating an EV [expected value], a zero value is a game changer” because zero multiplied with any probability always results in an EV of zero. Because zero outcomes reduced the sheer number of outcome-probability multiplications required to compute an EV, zero outcomes were apparently easier and quicker to process and drew less attention than maximum outcomes. This observation was at odds with predictions derived from the priority heuristic (Brandstätter, Gigerenzer, and Hertwig 2006). According to this account, minimum outcomes are the most important cues and should be viewed more frequently than maximum outcomes. Yet, Schulte-Mecklenbeck et al. (2017, 1008) reported a reverse pattern and concluded that “it remains a challenging task to decide whether the special role of the zero outcome is derived from its calculation consequences or from its processing priority”.

An alternative explanation for neglecting zero outcomes is based on the zero effect. Besides simplifying the choice set, zero outcomes are not worthy of being considered in a gain frame, as they do not provide any desirable value. Zero-averse decision makers may actively disregard zero outcomes to deploy attention to more attractive information instead. This attention allocation process would be functional when zero outcomes, in otherwise gains-oriented decision environments, were interpreted like losses. In this case, zero outcomes could be ignored without regret, and attention deployed to other gambles.

The two explanations for reduced attention on zero outcomes are not mutually exclusive. It is likely that both mechanisms jointly shape attention processes in risky choices. But the two accounts yield different predictions regarding the affective and motivational processes triggered by zero outcomes. Under the assumption that zero outcomes are simply easier and quicker to process because they do not require integration with probabilities, one would not expect these outcomes to generate any particular affect or (approach/avoidance) motivation. If decision makers eschew (or approach) zero-outcome gambles due to a strong aversion (attraction) to zero outcomes, depending on the given domain, higher arousal could be expected.

Indeed, there is evidence that emotional stimuli, like negative words or pictures, are easier to process than neutral stimuli (Scott, O'Donnell, and Sereno 2012; Ludwig, Dignath, and Lukas 2021). Affective responses might further facilitate the ease of processing zero-outcome gambles. There seems to be no research so far that considers these complementary explanations for selective attention on zero outcomes. Moreover, there are only few studies that explicitly address the zero effect in risky choices (Incekara-Hafalir, Kim, and Stecher 2021; Reyna et al. 2021; Zhang and Slovic 2019). Previous studies mostly included lottery choices that potentially confounded the zero effect and the certainty effect (e.g., Kahneman and Tversky 1979). Hence, this earlier research could not disentangle the unique contributions of both biases.

4 | Present Research

Our work went beyond Incekara-Hafalir, Kim, and Stecher's (2021) experiment in two important ways. First, we explored the zero effect in both the gain domain (Experiment 1) and the loss domain (Experiment 2). Second, our experiments investigated attentional and affective decision processes in addition to behavioral choices. To analyze these processes, we tracked eye movements and changes in pupil size.

We tracked eye movements to measure pre-decisional information search and examined pupil dilations to get a richer data basis for our hypotheses on responses to sure gains and zero outcomes in the gain domain and the loss domain. We tested if specific gamble attributes would dominate information acquisition. The process data (fixations of gamble attributes, pupil dilations) served to elucidate the psychological mechanisms driving the allocation of attention to zero outcomes in five types of gambles. Table 1 summarizes the key features of each lottery type. Our main predictions and results from two experiments are summarized in Table 2.

4.1 | Hypotheses

We proposed that zero outcomes would trigger affective responses that modulate attention allocation. Based on prior eye-tracking work on decisions under risk (Brandstätter and Körner 2014; Franco-Watkins and Johnson 2011; Glöckner and Herbold 2011; Ludwig, Jaudas, and Achtziger 2020; Pachur et al. 2018; Schulte-Mecklenbeck et al. 2017), we expected the following patterns of choice proportions, decision times, eye movements, and pupil dilations.

In short, we expected that decision makers would be motivated to avoid zero outcomes in the gain domain due to a highly

arousing, negative affective response. Likewise, for the loss domain, we predicted approach of zero outcomes driven by positive affect. Below, we provide more details on each outcome, addressing the gain domain (Experiment 1) first and the loss domain (Experiment 2) second.

4.1.1 | Lottery Choices

In the gain domain (Experiment 1), zero outcomes should elicit negative affect and trigger avoidance motivation. We therefore predicted choice proportions for zero-outcome lotteries (Types IV and V; see Table 1) to be reduced substantially below the probability of 0.50 (participants always choose between two options). Incekara-Hafalir, Kim, and Stecher (2021) challenged the certainty effect by demonstrating that an expected utility model combined with the certainty effect (modeling attraction to sure gains) did not outperform the expected utility model alone. Following their argument, but contradicting Kahneman and Tversky (1979), we expected that zero-variance lotteries with sure gains (probability of 1, Type II) would not be selected more often than by chance. To the extent that participants infer a sure gain from a gamble with two equal outcomes (see Section 5), choice proportions for Type II lotteries should be close to 0.50. In contrast, a typical certainty-effect prediction is that people prefer sure gains over risky gambles, resulting in increased choice proportions for the sure gain.

In addition, we included lotteries with a very high probability of winning ("almost sure gains," with a probability of 0.98 or 0.99, Type III). Type III lotteries are not zero-variance lotteries and therefore, by definition (Wakker 2010), should not trigger choice behavior consistent with the certainty effect. We included these lotteries mainly as a direct comparison to the zero-variance (Type II) lotteries. If Type II zero-variance lotteries had a special attraction for decision makers, introducing some variance

TABLE 1 | Lottery types and key features of the lottery tasks in Experiments 1 and 2.

Lottery type		Key features	Example (Exp. 1) $x, p; y, 1 - p$	Example (Exp. 2) $x, p; y, 1 - p$
I	SIM	All outcomes are very similar; the value of both gambles is similar according to CPT (cf. Glöckner and Betsch 2008; Glöckner and Herbold 2011)	A: 30, 0.70; 40, 0.30 B: 20, 0.60; 54, 0.40	A: -10, 0.50; -30, 0.50 B: -5, 0.60; -42, 0.40
II	CERT	Two equal outcomes for Gamble A (one sure gain) Exp. 1: Certainty-effect points to Gamble A Exp. 2: Certainty-effect points to Gamble B	A: 42, 0.55; 42, 0.45 B: 30, 0.40; 50, 0.60	A: -33, 0.50; -33, 0.50 B: -8, 0.60; -71, 0.40
III	ALM-CERT	One almost sure gain for Gamble A ($p = 0.98$ or 0.99)	A: 63, 0.99; 115, 0.01 B: 50, 0.55; 80, 0.45	A: -28, 0.98; -125, 0.02 B: -29, 0.50; -31, 0.50
IV	ZERO	One zero outcome for Gamble A Exp. 1: Zero-effect points to Gamble B Exp. 2: Zero-effect points to Gamble A	A: 94, 0.50; 0, 0.50 B: 76, 0.35; 32, 0.65	A: -48, 0.65; 0, 0.35 B: -25, 0.75; -49, 0.25
V	ZERO-ALM-CERT	One zero outcome and one almost sure gain for Gamble A Exp. 1: Zero-effect points to Gamble B Exp. 2: Zero-effect points to Gamble A	A: 9, 0.98; 0, 0.02 B: 5, 0.60; 15, 0.40	A: -40, 0.99; 0, 0.01 B: -21, 0.65; -74, 0.35

TABLE 2 | Overview of main predictions and empirical results in Experiments 1 and 2.

	Prediction	Gain/loss domain	Result
Lottery choice	Choice proportions for Gamble A in Type I lotteries will be close to and not statistically different from 0.50 (chance)	Gains (Exp. 1)	Supported
		Losses (Exp. 2)	Not supported
	Certainty effect: Choice proportions for Gamble A in sure gain lotteries (Type II) will be significantly larger than 0.50 (chance)	Gains (Exp. 1)	Supported
		Losses (Exp. 2)	Not supported
	Zero effect: Choice proportions for Gamble A in zero-outcome lotteries (Types IV and V) will be significantly smaller than 0.50 (chance)	Gains (Exp. 1)	Partially supported
		Losses (Exp. 2)	Partially supported
Decision time	Decisions in zero-outcome lotteries (Types IV and V) will be faster than decisions in lotteries without zero outcomes (Types I–III)	Gains (Exp. 1)	Supported
		Losses (Exp. 2)	Supported
Fixations	For zero-outcome lotteries (Types IV and V) there will be fewer fixations than for lotteries without zero outcomes (Types I–III)	Gains (Exp. 1)	Supported
	For zero-outcome lotteries (Types IV and V), there will be more fixations than for lotteries without zero outcomes (Types I–III)	Losses (Exp. 2)	Not supported
Pupil dilation	Changes in pupil size will be greater for zero-outcome lotteries (Types IV and V) than for Type I lotteries	Losses (Exp. 2)	Supported

Note: See Table 1 for more information on the key features of lottery Types I–V.

in Type III, even if very little, should notably impact choice behavior and decision processes. Moreover, we suspected that an almost sure gain might also be considered as particularly attractive by decision makers, in which case we would expect choice proportions larger than chance.

Finally, we expected choice proportions to be close to and not statistically different from 0.50 for Type I (SIM) lotteries (see Table 1 and Section 5), because the two gambles in Type I were alike in terms of probabilities and outcomes. The lotteries did not include extremely high or low outcomes (also no zero outcomes). They neither included probabilities outside the range between 0.25 and 0.75. No single gamble attribute was so salient that it would bias choices toward one or the other gamble.

What happens with losses? In Experiment 2, we expected the reverse pattern. Here, zero outcomes may be linked to comparatively low levels of negative affect. One might even expect zero outcomes to elicit some positive affect as they entail not losing any money. Thus, zero outcomes can appear as attractive in the loss domain, if the reference point has negative value. If zero outcomes were deemed as more attractive than alternative outcomes, their salience should increase, and choices would become more biased toward these outcomes in turn. Consequently,

choice proportions for zero-outcome lotteries (Types IV and V) were expected to be increased relative to the 0.50 chance level. If the certainty effect dominated choices in the loss domain, we would expect sure losses (with zero variance, Type II) to trigger avoidance behavior, resulting in lower choice proportions. By definition, the certainty effect would not be expected to generate similar choice patterns for gambles including almost sure losses (Type III). Finally, we expected choice proportions close to and not different from 0.50 in Type I lotteries.

4.1.2 | Decision Time and Fixations

Previous research argued that decision times indicated decision difficulty (Achtziger and Alós-Ferrer 2014; Ludwig, Ahrens, and Achtziger 2020; Schotter et al. 2010). If zero outcomes were processed more easily than other gamble attributes, decisions should be quicker for lotteries with zero outcomes (Types IV and V) compared to lotteries without zero outcomes (Types I–III). This decision time pattern would emerge in both domains (gain, loss).

A zero-effect perspective yields the same prediction. If attentional resources become available due to an automatic avoidance

response, zero-outcome lotteries should require less effortful information search than rather difficult Type I lotteries. Less effortful information search facilitates the decisions overall and choices between gambles may thus become faster in the presence of zero outcomes.

For visual fixations, we expected the zero effect to trigger attentional neglect of zero outcomes and their probabilities. Similar findings were reported previously (Glöckner and Herbold 2011; Schulte-Mecklenbeck et al. 2017). We intended to replicate these results. We expected that zero outcomes are identified rather effortlessly, and participants avoid these outcomes automatically (see Bateman et al. 2007; Finucane et al. 2000). Therefore, we predicted fewer fixations for lotteries with zero outcome (Types IV and V) compared to lotteries without zero outcomes (Types I–III).

For the loss domain (Experiment 2), we expected attention to be drawn toward zero outcomes. These outcomes were the most attractive ones in each lottery. We hypothesized that zero outcomes would be fixated more often than other attributes in the loss domain, because the hedonic quality of an outcome drives information acquisition (Karlsson, Loewenstein, and Seppi 2009). Yet, it could also be argued that the processing of zero outcomes is rather effortless and automatically instigates an approach response toward this outcome. In this case, zero outcomes would not attract more fixations than non-zero outcomes.

Our hypotheses on decision times and fixations can be inferred from the argument that (a) zero outcomes draw less attention than other outcomes because the expected value of zero outcome gambles is zero and (b) zero outcomes trigger avoidance responses. Yet, these approaches differ regarding arousal and motivational responses on zero outcomes. If zero outcomes were avoided due to an ostrich effect-like mechanism, they should be linked to negative affect and high levels of arousal (i.e., the intensity of the affect). Increased arousal would not be expected if zero outcomes were merely easier to process.

4.1.3 | Pupil Dilation

Pupillometry provided an opportunity to measure the affective processes driving the zero effect. Pupillary responses are influenced by various factors, for instance, cognitive effort (Kahneman and Beatty 1966; Alós-Ferrer, Jaudas, and Ritschel 2021b), arousal due to decision uncertainty (Urai, Braun, and Donner 2017), and cognitive conflict (van Steenbergen and Band 2013). Pupil size changes can also be interpreted as indicators of the intensity of an affective experience, or arousal more generally (e.g., Bradley et al. 2008; Hochman et al. 2016; Kinner et al. 2017).

Using a lottery choice paradigm like ours, Fiedler and Glöckner (2012) demonstrated that pupil dilations varied with lotteries' mean expected value (EVmean), presumably because higher EVmeans (i.e., larger gains on average) elicited higher arousal than lower EVmeans, as they represented more desirable outcomes. Given the multiple factors behind pupil size changes in decision making, it remained unclear if pupillometry could capture affective responses on specific gamble attributes

in lottery choices (e.g., increased arousal on zero outcomes compared to non-zero outcomes). Indeed, pupil size changes could track decision difficulty (cognitive effort or conflict) rather than outcome desirability (arousal).

In a study with comparable lotteries, zero outcomes were associated with increased pupil size, compared to lotteries without zero outcomes (Ludwig, Jaudas, and Achziger 2020). This effect remained robust when controlling for the mean expected value. From the decision time analysis, it was inferred that decisions in zero-outcome lotteries were on average easier than other lotteries. Under the assumption that pupillary responses primarily indicate decision difficulty, these findings were difficult to explain, because easier lotteries would then be expected to evoke smaller pupil size changes. This observation thus suggested that pupil size changes may not be a valid indicator of cognitive effort in risky choices.

We further examined pupil dilations related to our five lottery types. Because there was no clear argument which factor would dominate the pupillary response, we refrained from proposing hypotheses on pupil dilations in Experiment 1. However, we note that our analysis was guided by prior work suggesting that, in risky choices, pupils dilate as a function of arousal rather than cognitive effort (Ludwig, Jaudas, and Achziger 2020). We built on this finding to further investigate the role of affect in modulating pupillary responses in risky choices.

Based on the results of Experiment 1, we pre-registered hypotheses on pupil dilations for Experiment 2 (loss domain). We predicted that zero-outcome lotteries (Types IV and V) would elicit greater changes in pupil dilation than the remaining lottery types (Types I–III). This would be consistent with the argument that zero outcomes in the loss domain are processed like desirable outcomes. On the other hand, Type III lotteries might generate greater pupil size changes than Type I lotteries, because the former contain a large potential loss (even though with a very small probability of only 0.01 or 0.02; see Table 1 and Appendix).

5 | Method

Two experiments were run in the same laboratory, using the same equipment, had almost identical procedures, and very similar materials. We followed the local legislation and university regulations regarding ethical requirements for research involving human participants. The procedures were approved by the institutional review board. We report how we determined our sample size, all data exclusions (if any), all treatments, and all measures in our experiments. The materials, data, and the pre-registration of Experiment 2 are available at <https://osf.io/rzd8c>. Experiment 1 was not pre-registered.

5.1 | Design

The experiments followed a within-subjects design with one factor (Lottery Type). The key features of five lottery types are summarized in Table 1 (see also Tables S1 and S2 for the complete list of lotteries). There were 10 lotteries per type; hence,

each participant made 50 choices. We recorded choices, decision times, eye movements, and pupil dilations as the dependent variables. A further factor for the analysis of fixations was the lottery outcome (within-subjects, Gamble A outcomes: A1, A2; Gamble B outcomes: B1, B2). We explored how fixations were distributed over time across the four outcomes of a lottery to assess if zero outcomes received the same attention as other outcomes. For the pupillometric analyses, we added the lotteries' mean expected value as a predictor since prior work reported that it is linked to pupil dilations (Fiedler and Glöckner 2012).

5.2 | Participants

For Experiment 1, we determined a target sample size of 33 participants prior to data collection. The sample size was in line with comparable eye-tracking studies (Fiedler and Glöckner 2012; Franco-Watkins and Johnson 2011; Perkovic, Bown, and Kaptan 2018; Smith and Krajbich 2019). We anticipated data exclusions due to poor data quality or software errors. In our laboratory, roughly 10% of participants are usually excluded due to these kinds of errors. Hence, 36 participants (16 female; $M_{\text{age}} = 22.49$ years, $SD = 3.03$) were invited for individual sessions. One participant was excluded due to technical problems with the eye-tracker, so the final sample size was $N = 35$. We compensated participation with €3 plus an additional payment contingent on the outcomes in the decision task, based on a random lottery incentive system. Participants were informed that one of the lotteries would be chosen and played by the computer and that their additional payment would be determined by the outcome of this lottery (range: €0.90 to €9.00, $M_{\text{Payment}} = €4.17$, $SD = 2.44$).

For Experiment 2, the sampling plan, hypotheses, and analysis plan were pre-registered (<https://osf.io/rzd8c>). Our analyses deviate from the pre-registration. Instead of analyzing choices via ANOVA, Section 6 reports a more appropriate logistic mixed-effect model. This time, we collected data from 43 participants. Seven data sets were excluded due to technical issues or inferior data quality. The final sample size was $N = 36$ (14 female; $M_{\text{age}} = 21.92$ years, $SD = 2.51$). Participants in Experiment 2 were endowed with €19 at the beginning of the study and told that one randomly chosen lottery would determine the amount of money to be deducted from the endowment (range: €0 to € −11.00, $M_{\text{Deduction}} = € −4.07$, $SD = 2.35$).

5.3 | Procedure and Materials

Participants were screened for involvement in similar research and hard contact lenses, which interfered with eye-movement measurements. Participants gave written informed consent prior to data collection. Following detailed instructions on the lottery task, we familiarized them with the eye-tracker, a tower-mounted monocular SMI iView X Hi-Speed tracker, sampling at a 240 Hz rate. All participants had normal or corrected-to-normal vision. An LCD monitor (AOC LM927U, refresh rate 60 Hz, resolution 1280 × 1024) was located 700 mm in front of the eyes. We used SMI iView X 2.2 software to record gaze data. Choices and decision times were

measured by Presentation 17.1 (Neurobehavioral Systems, Albany, CA, USA).

The lottery choice task covered five types of lotteries designed to enable an independent analysis of the certainty effect and the zero effect. Based on eight (Type I, SIM) lotteries taken from Glöckner and Herbold (2011) (see also Glöckner and Betsch 2008), we designed 10 lotteries for each type, resulting in 50 lotteries (see Table 1 for an overview of the lottery types' key features and Tables S1 and S2 for the entire set). An example is displayed in Figure 1. Each lottery consisted of two gambles (Gamble A on the left and Gamble B on the right). Each gamble described the chance to gain a specified amount of experimental currency units (E) with a probability p or the chance to gain an alternative amount of E with a probability $1 - p$. Probabilities within one gamble always added up to 1. The EVmeans of gambles in a lottery were close or alike. Thus, we ruled out that preferences for one gamble were based on EVmean differences.

The first lottery type (SIM) included gambles with very similar outcomes and probabilities (Experiment 1: outcomes ranged from 50 to 69 E and probabilities from 0.40 to 0.60 in one lottery of this type). According to CPT (Kahneman and Tversky 1979; Tversky and Kahneman 1992), both gambles had very similar subjective utilities (Glöckner and Herbold 2011; see Glöckner and Betsch 2008 for more detail on the subjective utility calculations and generation of Type I SIM lotteries). We expected that participants would choose Gamble A/B equally often, resulting in a 0.50 choice proportion for Gamble A in both experiments.

Type II lotteries included a sure gain/loss in one gamble. To that end, two equal outcomes were displayed in Gamble A. The outcomes were of equal magnitude with varying probabilities of winning (Experiment 1) or losing (Experiment 2). Probabilities added up to a sure gain/loss (i.e., 100%) for Gamble A. If participants were attracted by certainty, the certainty effect suggested choosing Gamble A in Experiment 1 (gain domain) but avoiding Gamble A in Experiment 2 (loss domain).

Importantly, Type II lotteries did not invariantly also include a zero outcome in the other gamble. If decision makers preferred the sure gain over a risky gamble in this lottery type, we concluded that this preference relied on the desirability of the sure gain. Zero outcomes were not included in Type II lotteries, thereby ruling out that the zero effect pushed choices toward the sure gain.

Type III lotteries had an almost sure gain in one gamble. The probability of winning was 0.98 or 0.99 in Gamble A. By definition, the certainty effect (Wakker 2010) applies only to zero-variance lotteries. Hence, we would not expect a particular attraction (Experiment 1) or avoidance (Experiment 2) of Type III lotteries under the assumption of a certainty effect. Introducing some variance, even if only very little, should eliminate any certainty biases.

Lottery Types IV and V contained a zero outcome in Gamble A. Zero-outcome avoidance thus motivated to eschew Gamble

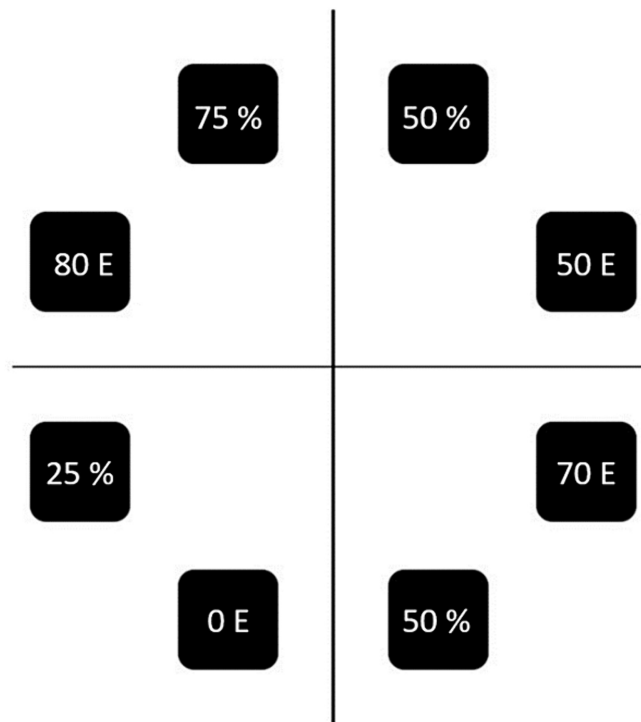


FIGURE 1 | Example of a Lottery Type IV (ZERO), Experiment 1. *Note:* Gamble A is displayed on the left side, and Gamble B on the right side. Locations of probabilities and outcomes varied randomly between trials. See Tables S1 and S2 for the complete list of lotteries presented in Experiments 1 and 2.

A in Experiment 1 but to choose this gamble in Experiment 2. The difference between these two lotteries was that Type V had one zero outcome and one almost sure gain (with a 0.98 or 0.99 probability of winning) in the same gamble. To the extent that an almost sure gain might be considered as an attractive outcome, Type V lotteries created a conflict between opposing motivations of zero-outcome avoidance and attraction to an almost sure gain contained within the same gamble.

The task was essentially the same in both experiments, but all outcomes were framed as gains in Experiment 1 and as losses in Experiment 2. The lotteries in Experiment 2 were adjusted with minor changes to match the average EVmean of the five lottery types. In Experiment 1, the average EVmean across the 10 lotteries within each type was comparable for Types III–V, but it was substantially higher for Type I–II lotteries (see Table S1). The lotteries were altered in Experiment 2 in a way that all lottery types had almost the same average EVmean when aggregating across the 10 lotteries of each type.

All lotteries were presented in randomized order. The locations of Gamble A and B (left, right) and the locations of gamble attributes (outcome, probability) within quadrants were randomized in each trial. Hence, information on outcomes and probabilities did not always appear on the same spot, and participants could not get used to processing outcomes and probabilities in a particular sequence. They were required to stay focused and actively search for information.

A blank screen (2000ms) and fixation cross (1000ms) preceded each lottery. The eight pieces of information per lottery (i.e., two outcomes and two probabilities per gamble) were displayed

in white font framed by a black square (110×110 pixels; see Figure 1). Each information had the same distance to the center of the screen. Areas of interest (AOIs) were defined somewhat larger than the black frame (179×105 pixels per AOI) around each outcome/probability attribute. Participants chose a gamble (left or right) by pressing the respective button on a Cedrus RB-530 response pad.

After the lottery choice task, participants provided demographic information and, in Experiment 1, answered three open questions on whether they used any specific choice strategy (one open-ended question on choice strategy in Experiment 2). Finally, participants were thanked, debriefed, and paid according to their individual earnings in the task.

6 | Results

Our analyses focused on mixed-effect models with lottery type (I–V) as fixed effect, random intercepts for lotteries and participants, and by-subject random slopes for lottery type. We computed likelihood ratio tests (LRT) to compare the lottery type model to a reduced model with only the random effects to assess the impact of the lottery type fixed effect on the dependent variables. For each model, Type I was entered as the reference category so that model estimates for the remaining lottery types specified a comparison of the respective type to Type I. All models were fitted with R using the glmer (choices) and lmer functions (decision times, fixations, pupil dilation) from the lme4 package (Bates et al. 2015; R Core Team 2022). Linear models were fitted with ML and logit models using Laplace approximation.

Single trials were excluded prior to the analyses if the logarithmized decision time ($\log[\text{RT}]$) was three standard deviations above or below the mean of the $\log(\text{RT})$ distribution. We excluded eight trials (0.46% of all trials of all participants) in Experiment 1 (Experiment 2: 17 trials; 0.94%). Thus, we analyzed 1742 observations in Experiment 1 and 1783 observations in Experiment 2.

The report is structured as follows. We first analyzed lottery choices to disentangle the unique contributions of the certainty effect and the zero effect to decisions under risk. We then addressed decision times and the number of fixations to test if zero outcomes rendered choices quicker and easier to process. Next, we examined the distribution of fixations across the four outcomes of each lottery type separately to replicate the prior finding that zero outcomes receive a smaller share of visual attention than non-zero outcomes (Brandstätter and Körner 2014; Franco-Watkins and Johnson 2011; Glöckner and Herbold 2011; Ludwig, Jaudas, and Achtziger 2020; Schulte-Mecklenbeck et al. 2017). We then explored the reacquisition frequencies of zero outcomes, addressed pupil dilation changes over time, and, finally, examined the relations among these measures in additional exploratory analyses.

6.1 | Lottery Choices

Choice proportions for the lottery types in both experiments are displayed in Figure 2. Table 3 provides the main variables' descriptive statistics.

6.1.1 | Experiment 1 (Gains)

A logit mixed-effect model for choices (coded 1 for Gamble A) yielded a significant effect of lottery type, $\chi^2(4) = 46.41$, $p < 0.001$. Choice proportions for Gamble A differed from Type I lotteries only for Type IV (ZERO) lotteries, $OR = 0.08$, 95% confidence interval [0.03, 0.18], $p < 0.001$. Descriptively, choice proportions were also reduced for Type V, $OR = 0.52$ [0.27, 1.03], $p = 0.060$, but missed significance. Hence, gambles with zero outcomes were

chosen less often, consistent with the zero-effect prediction. Choice proportions were not increased for lotteries with a sure gain, Type II $OR = 1.32$ [0.82, 2.11], $p = 0.254$, and lotteries with an almost sure gain, Type III $OR = 1.64$ [0.94, 2.90], $p = 0.082$. Hence, neither sure gains nor almost sure gains were chosen more often than the reference Type I lotteries. Note however (see also Figure 2 and Table S3) that the sure gain gamble in Type II lotteries was chosen more often than chance. Experiment 1 thus produced inconclusive results regarding the certainty-effect.

6.1.2 | Experiment 2 (Losses)

Choice proportions in Experiment 2 largely supported our ideas. Lottery type predicted choices, $\chi^2(4) = 12.30$, $p = 0.016$. Both zero-outcome categories (Type IV, $OR = 2.49$ [1.37, 4.52], $p = 0.003$, and Type V, $OR = 1.67$ [1.00, 2.77], $p = 0.048$) had increased choice proportions for Gamble A relative to Type I. This observation was consistent with the prediction that zero outcomes would appear particularly attractive in a loss frame. Inconsistent with the certainty-effect prediction, choice proportions for Gamble A were not different from Type I in the certainty-effect category Type II, $OR = 1.13$ [0.66, 1.94], $p = 0.645$, or from the 0.50 chance level (see also Table S3). Almost sure losses did also not result in choice proportions different from Type I, Type III $OR = 0.96$ [0.57, 1.61], $p = 0.886$, but were chosen less frequently than chance. In conclusion, there was no clear support for a certainty effect in the loss domain, resembling results in the gain domain.

6.2 | Decision Times and Fixations

Mean decision times and number of fixations per decision and lottery type are shown in Table 3. Decision times were log-transformed to reduce skewness.

6.2.1 | Experiment 1 (Gains)

Lottery type determined decision times, $\chi^2(4) = 46.58$, $p < 0.001$. Relative to Type I lotteries, decisions were faster for

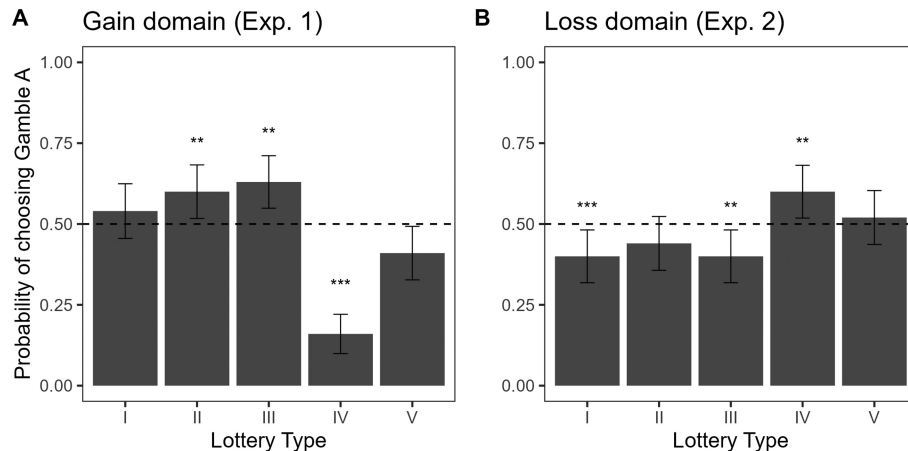


FIGURE 2 | Choice proportions of five lottery types in (A) Experiment 1 (gain domain) and (B) Experiment 2 (loss domain). Note: The dashed line marks the 0.50 chance level of choosing Gamble A. Error bars indicate the standard error of the mean. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, for one-sample t -test against the 0.50 chance level (see Table S3 for test statistics).

TABLE 3 | Summary of descriptive statistics (mean, standard deviation in parentheses) of the main dependent variables in Experiment 1 (gain domain) and Experiment 2 (loss domain).

		Type I SIM	Type II CERT	Type III ALM-CERT	Type IV ZERO	Type V ZERO-CERT
Exp. 1	Probability Choice A	0.54 (0.50)	0.60 (0.49)	0.63 (0.48)	0.16 (0.36)	0.41 (0.49)
	Decision time	13.86 (7.45)	12.84 (6.11)	11.93 (5.97)	10.62 (6.20)	9.84 (5.19)
	Number of fixations	43.21 (24.73)	38.25 (18.04)	35.95 (17.69)	31.56 (17.56)	29.20 (15.64)
Exp. 2	Probability Choice A	0.40 (0.49)	0.44 (0.50)	0.40 (0.49)	0.60 (0.49)	0.52 (0.50)
	Decision time	15.92 (9.32)	15.75 (9.86)	13.85 (7.62)	14.80 (8.82)	13.96 (8.82)
	Number of fixations	46.45 (26.39)	44.87 (27.31)	39.68 (21.80)	42.12 (24.85)	40.39 (22.32)

all other lottery types, except for sure gain Type II lotteries. Only for Type II, log (RT) did not differ from Type I, $b = -0.02$ $[-0.06, 0.02]$, $p = 0.274$. Log (RT) was reduced for Type III by -0.06 $[-0.09, -0.02]$, $p = 0.002$; for Type IV by -0.13 $[-0.18, -0.08]$, $p < 0.001$; and for Type V by -0.15 $[-0.19, -0.11]$, $p < 0.001$. Thus, decisions were slowest for Type I–II lotteries and fastest for Type IV–V lotteries, linking zero outcomes to expedited choices.

The fixation analysis was in accordance with decision times. As expected, difficult (Type I) lotteries generated the most fixations and the slowest decisions, whereas lotteries that included a zero outcome (Types IV and V) generated fewer fixations. Lottery type determined the number of fixations, $\chi^2(4) = 35.37$, $p < 0.001$. Relative to Type I, there were fewer fixations for all other lotteries. The average number of fixations was reduced in Type II by -4.96 $[-9.07, -0.85]$, $p = 0.018$; in Type III by -7.26 $[-10.94, -3.58]$, $p < 0.001$; Type IV by -11.65 $[-16.25, -7.05]$, $p < 0.001$; and Type V by -14.01 $[-18.54, -9.47]$, $p < 0.001$.

6.2.2 | Experiment 2 (Losses)

The mixed-effect regression estimates suggested that only choices in lotteries with almost sure losses (Type III and Type V) were faster than Type I, $b = -0.12$ $[-0.23, -0.02]$, $p = 0.025$ and $b = -0.14$ $[-0.25, -0.04]$, $p = 0.008$, respectively. Log (RT) of Types II and IV largely resembled response times for Type I lotteries, $b = -0.03$ $[-0.14, 0.08]$, $p = 0.598$, and $b = -0.08$ $[-0.18, 0.02]$, $p = 0.114$, respectively. The LRT for lottery type was not significant, $\chi^2(4) = 8.20$, $p = 0.085$.

Like Experiment 1, the analysis of fixations was in line with decision time patterns. The LRT for lottery type was not significant, $\chi^2(4) = 7.42$, $p = 0.115$. The model revealed fewer fixations for Type III lotteries, with a reduction by -6.89 $[-12.65, -1.14]$, $p = 0.019$, and for Type V, $b = -6.51$ $[-11.74, -1.29]$, $p = 0.015$. Type IV zero outcomes seemed to generate fewer fixations than Type I, $b = -4.37$ $[-9.13, 0.40]$, $p = 0.072$, but the difference was not significant. The number of fixations in Type II lotteries (sure losses) did not differ from Type I, $b = -1.70$ $[-6.82, 3.42]$, $p = 0.514$. In sum, in the loss domain, there was no clear support for the decision time and fixation predictions based on either the zero effect or the certainty effect.

6.3 | Attention to Gamble Attributes

To examine if the reduction of the overall number fixations for zero-outcome lotteries (especially in the gain domain) could be attributed to the quality of these particular outcomes, we compared the fraction of fixations that were directed at the four outcomes of each lottery. If a reduction of the overall number of fixations in the presence of zero outcomes could be traced back to zero outcome, we would expect a smaller share of fixations on zero outcomes than on any other outcome displayed at the same time. This pattern was reported previously (Glöckner and Herbold 2011; Pachur et al. 2018; Schulte-Mecklenbeck et al. 2017) and could be expected if zero outcomes draw less attention than other non-zero outcomes. The reason could be that zero outcomes are processed effortlessly, either (a) because they do not require processing probabilities or (b) because of a motivational avoidance process triggered by these outcomes.

6.3.1 | Experiment 1 (Gains)

We replicated the finding of fewer fixations on zero outcomes in the gain domain. Figure 3 shows the distribution of fixations across the four outcomes per lottery. In Type I lotteries, fixations were distributed nearly equally to the four outcomes, that is, each of the four outcomes per lottery received around 25% of all fixations. This observation was consistent with our assumption that SIM lotteries were difficult to process because the attributes were quite similar. No single outcome attracted relatively more attention than the others.

We estimated linear mixed-effect models for each lottery type separately, entering outcome (A1, A2, B1, B2) as a fixed effect, a random intercept for participants, and by-subject random slopes for outcome. As expected, the fixed effect of outcome was not significant for Type I, $\chi^2(3) = 3.78$, $p = 0.286$. For the remaining types, our analysis revealed significant deviations from a uniform distribution of fixations (see Table S4). Most importantly, zero outcomes were less frequently fixated than other outcomes in zero-outcome (Type IV and V) lotteries, see also Figure 3. For instance, the effect of outcome was significant for Type IV, $\chi^2(3) = 28.78$, $p < 0.001$, with zero outcomes (A2) drawing -8.50 $[-11.25, -5.75]$, $p < 0.001$, percentage points fewer fixations than A1 (moderate gains).

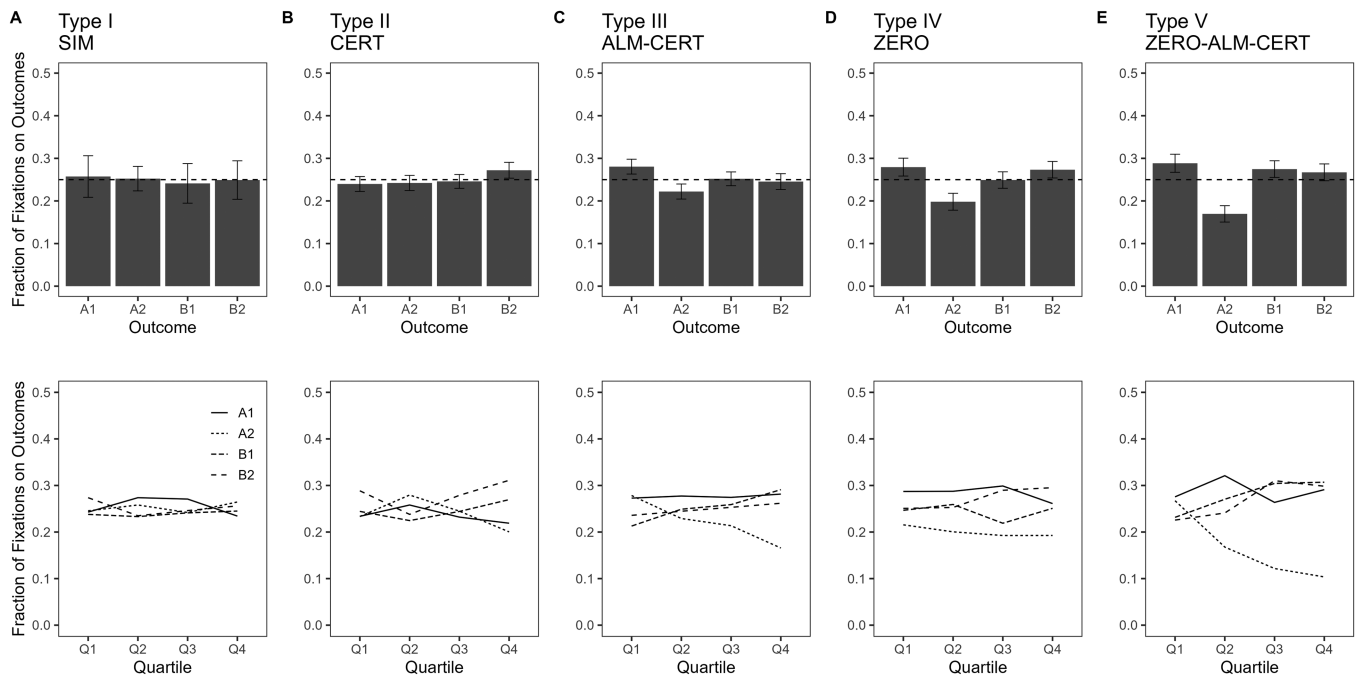


FIGURE 3 | Fraction of fixations on four lottery outcomes (A1, A2, B1, B2; upper panel) and across decision time quartiles (Q1, Q2, Q3, Q4; lower panel) in Experiment 1 (gain domain). *Note:* Figure S1 contains the corresponding plots for Experiment 2. The upper panels show the fraction of fixations on each outcome, separately for each lottery type (Panels A–E for lottery types I–V, respectively). The dotted line denotes equal distribution of fixations on outcomes, that is, 25% for each outcome. Error bars indicate the standard error of the mean. The lower panel shows how the fraction of fixations on each outcome changed over time, presented for quartiles of the decision time. Type I lotteries had very similar outcomes; Type II lotteries had two outcomes of the same value (i.e., one sure gain); Type III had an almost sure gain with very high probability (0.99 or 0.98; outcome A1) and an outcome with a very low probability (0.01 or 0.02; outcome A2); Type IV included a zero outcome (outcome A2); Type V had both a zero outcome (outcome A2) and an almost sure gain (outcome A1).

Next, we assessed if attention allocation to zero outcomes changed over time. One might expect that zero outcomes will be fixated about as often as other outcomes at the beginning of a trial but could be neglected at later stages. Fixation frequencies of zero outcomes, then, should drop over time. Alternatively, zero outcomes could draw relatively little attention from the very beginning of a trial; hence, fixation frequencies would hardly vary over time. To explore these possibilities, we split the time a trial lasted into quartiles (Q1, Q2, Q3, Q4) based on the decision time of this specific trial. We then examined how fixations were allocated to the four outcomes in each quartile.

Figure 3 shows that zero outcomes in Type IV were less frequently fixated than A1 outcomes already in Q1, $b = -6.94$ $[-11.75, -2.13]$, $p = 0.005$. This difference was stable over time and persisted until Q4, where zero outcomes drew -6.50 $[-10.98, -2.01]$, $p = 0.005$, percentage points fewer fixations than A1 outcomes. Another interesting observation was that in Q1, Type V zero outcomes received about the same share of attention as other outcomes, but fixations on zero outcomes (A2) then dropped over the remaining quartiles. A similar pattern was observed in Type III lotteries. Here, attention to A2 outcomes (medium outcomes linked to very small probabilities of 0.01 or 0.02) dropped over time. For detailed comparisons of fixations between time windows Q1 and Q4, see Tables S6 and S7.

6.3.2 | Experiment 2 (Losses)

A similar pattern of fixations emerged in the loss domain. Type I lotteries had a uniform distribution of fixations to the four outcomes (A1, A2, B1, B2), $\chi^2(3) = 3.15$, $p = 0.370$. Like in Experiment 1, the fixed effect of outcome was significant for the remaining types. Table S5 provides the mixed-effect regression estimates for each lottery type (see also Figure S1). Most interesting was that zero outcomes were less often fixated than other outcomes, just as observed in Experiment 1. For example, zero outcomes (A2) in Type IV caught -7.35 $[-9.64, -5.06]$, $p < 0.001$, percentage points fewer fixations than A1 (moderate losses) in the same lottery.

A quartile-wise analysis of re-acquisition frequencies of zero outcomes revealed that zero outcomes were not fixated less often than A1 outcomes in Q1, $b = 1.23$ $[-3.80, 6.26]$, $p = 0.632$. But over time, attention to zero outcomes decreased, and in Q4, zero outcomes drew -5.39 $[-9.16, -1.62]$, $p = 0.005$, percentage points fewer fixations than A1 outcomes.

6.4 | Pupil Dilation

We analyzed the first 5000 ms of each trial (i.e., pupil dilation measured from the beginning of a lottery's presentation until 5000 ms). We divided each trial into 50 bins of 100 ms

and computed the percentage of pupil size change relative to a pre-stimulus baseline for each trial (see, e.g., Fiedler and Glöckner 2012; Ludwig, Jaudas, and Achziger 2020). The baseline was determined for each trial separately as the median pupil dilation during 500 ms before the lotteries appeared on the computer screen (preceded by a fixation cross). Figure 4 shows the mean percentage of pupil size change dependent on lottery types in Experiment 1. Visual inspection of the figure suggested that pupil size developed similarly for the five lottery types until approximately 1000 ms but differed notably afterward. This lag in pupillary response to an eliciting stimulus was typical because changes in pupil dilation are slow (Cavanagh et al. 2014; Kinner et al. 2017; van Steenbergen and Band 2013).

To assess if the lottery type affected pupil size change, we analyzed the percentage of change relative to the baseline. Lottery type and bin were entered as fixed effects, and we included random intercepts for lotteries and participants and by-subject random slopes for lottery type. Prior work indicated that pupil size changed as a function of the lotteries' EVmeans (Fiedler and Glöckner 2012; Ludwig, Jaudas, and Achziger 2020), so we added EVmean as an additional fixed effect.

6.4.1 | Experiment 1 (Gains)

As expected, EVmean affected pupil size change, $\chi^2(1)=5.92$, $p=0.015$, with higher EVmean predicting greater changes in pupil dilation, $b=0.01$ [0.00, 0.02], $p=0.012$. Most importantly, there was a significant interaction between lottery type and bin, $\chi^2(4)=45.77$, $p<0.001$, consistent with the idea that pupil size changed distinctly over time for the five lottery types. All lottery types lead to greater pupil size changes than Type I lotteries (see Table S8 for details). To further explore this interaction, we estimated separate mixed-effect models with lottery type as fixed effect for each bin. Lottery type was a significant predictor only between Bins 15–25 (between 1500–2500 ms) and Bins 44–50 (4400–5000 ms; see Figure 4).

For example, in Bin 20 (2000 ms after stimulus onset), lottery type predicted pupil size change, $\chi^2(4)=10.19$, $p=0.037$. Compared to Type I lotteries, three types evoked greater changes in pupil dilation: Type III was associated with increased pupil size by 1.35 [0.50, 2.21], $p=0.002$, Type IV with 1.04 [0.18, 1.89], $p=0.017$, and Type V with 1.05 [0.10, 2.01], $p=0.031$. Only Type II lotteries did not differ from Type I, $b=0.52$ [−0.34, 1.38], $p=0.238$.

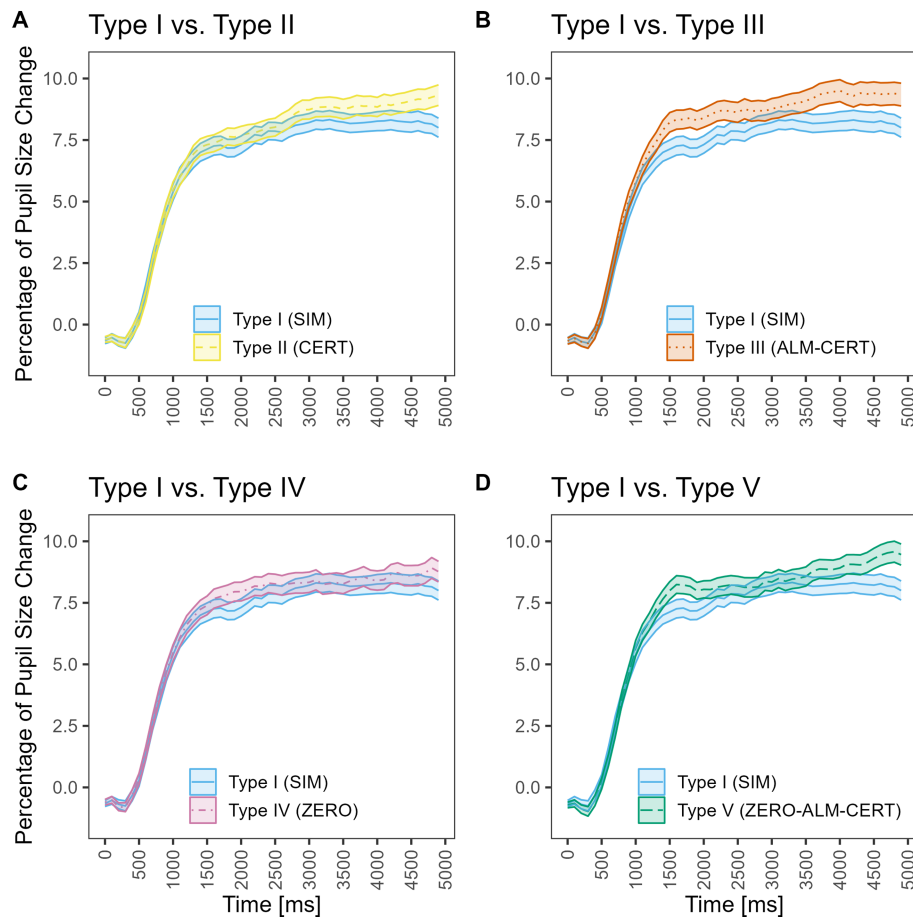


FIGURE 4 | Percentage of pupil size change over time in Experiment 1 (gain domain). *Note:* Figure S2 contains the corresponding plots for Experiment 2. The shaded areas represent the standard error of the mean. Pupil size changes over time are relative to a pre-stimulus baseline. Panels A–D show the comparison of Lottery Types II–V to Type I, respectively. Type I lotteries had very similar outcomes; Type II had a sure gain; Type III had an almost sure gain; Type IV included one zero outcome; Type V had both a zero outcome and an almost sure gain.

Our observations were consistent with the idea that pupil dilations on economic decisions reflected arousal rather than cognitive effort. If cognitive effort was the main driver of pupillary responses, greater changes in pupil dilation would be expected for Type I lotteries compared to the other lottery types. Type I lotteries were the most difficult ones, as indicated by slower decisions and higher numbers of fixations. Inconsistent with the notion that pupil dilations reflect cognitive effort, we observed that pupils dilated more with relatively easier lotteries (see Table 3 for decision times).

To the extent that changes in pupil dilation reflected affective responses to lotteries' outcomes rather than the cognitive effort required to process the lotteries, our results implied that relative to Type I, all other lottery types were associated with increased affective arousal. This pattern would not be expected if zero outcomes received less attention than other outcomes merely because they were easier to process. Rather, the observation is consistent with zero outcomes eliciting negative affect and avoidance motivation.

6.4.2 | Experiment 2 (Losses)

We conducted the same analyses for the loss domain. Like Experiment 1, we observed an interaction between lottery type and bin, $\chi^2(4)=73.24$, $p<0.001$, suggesting that pupil sizes changed distinctly over time for the different lottery types. The analysis suggested that, relative to Type I, all lotteries except for Type III were associated with greater pupil size changes (Table S8 and Figure S2). This was in line with our above argument that pupil size changes in risky choices traced affective arousal rather than cognitive effort. The reason was that the most difficult lotteries (Type I) resulted in comparatively smaller changes in pupil size than other lottery types, just like Experiment 1 (see also Figure S2).

However, the impact of lottery type was less clear in Experiment 2 (loss domain) than in Experiment 1 (gain domain). Bin-wise analyses followed up on the interaction and suggested that lottery type was a predictor only in Bin 45 (4500 ms after stimulus onset), $\chi^2(4)=10.05$, $p=0.040$. This observation limited our conclusions for the loss domain. Note that EVmean did not predict pupil size changes in the loss domain, $\chi^2(1)=0.11$, $p=0.737$.

6.5 | Further Exploratory Analyses

To afford a deeper exploration of the relations among our main dependent measures and to gain further insight into the zero effect as the driving factor behind the above reported results, we conducted two additional exploratory analyses. These analyses are summarized in Figure 5.

First, we examined choice proportions separately for trials with comparatively high versus low number of fixations. Given that zero outcomes are attended to much less frequently than other outcomes, one might expect the behavioral zero effect on lottery choices to be particularly pronounced when decisions are based on fewer fixations overall. To analyze this proposition, we

determined, per lottery type, the median of the average number of fixations per trial, and categorized trials as either above or below the median. Next, we compared choice proportions for Gamble A across trials with higher (above median) or lower (below median) numbers of fixations; see Panels A (Exp. 1) and B (Exp. 2) of Figure 5. In the gain domain (Exp. 1), we found for Type IV lotteries with zero outcomes that choice proportions for Gamble A dropped significantly, to 5.20%, in trials with fewer fixations than the median of this lottery type (Table S9 provides descriptive and test statistics; the difference between the median-split groups was also significant for Type I and III lotteries). This observation suggested a stronger zero effect when decisions were based on only few fixations. However, the same pattern did not emerge in the loss domain (Exp. 2).

Second, we examined the pupil size change over time in Type IV zero-outcome lotteries separately for trials in which participants chose Gamble A, which contained the zero outcome, or Gamble B. Though we counted much fewer trials with choices for the zero-outcome gamble in Experiment 1 (see also Figure 2), it is remarkable that we recorded significantly larger changes in pupil size over time when participants opted for the zero outcome; see Panel C of Figure 5 (and Table S10 for test statistics). In the loss domain, choices for the zero-outcome gamble were associated with significantly smaller increases in pupil size change over time; see Panel D of Figure 5 and Table S10. These observations are consistent with the interpretation that decision makers experienced choosing a zero outcome in the gain domain as more aversive than not doing so, whereas in the loss domain, they experienced choosing the zero outcome as less aversive than not doing so. We note, however, the exploratory nature of these analyses.

7 | Discussion

We have demonstrated a robust zero effect on decisions under risk, indicating that decision makers faced with risky gambles were motivated to avoid zero outcomes when all other outcomes were gains (Experiment 1) but more frequently chose zero outcomes when all other outcomes were losses (Experiment 2). They did so quicker than in difficult trials in which the two gambles were quite similar in terms of outcomes and their probabilities (Type I). Decision makers in both gain and loss domains allocated less attention to lotteries if zero outcomes were included. Together, our findings were consistent with the view that zero-outcome avoidance in the gain domain and preferences for zero outcomes in the loss domain relied on automatic processes triggered rather effortlessly by zero outcomes. Our observations largely aligned with a pronounced zero effect on attention and choice that applies to both gain and loss frames. But note that not all effects reached significance in Experiment 2, so the evidence was stronger for the gain domain.

The discrepancy between Experiments 1 and 2 could have several reasons. Losses are generally experienced as more arousing than equivalent gains (Sokol-Hessner et al. 2009). Higher overall arousal levels in Experiment 2 could have blurred subtle arousal differences triggered by distinct outcomes like zero outcomes or sure losses. This might be one reason why differences between lottery types were more difficult to detect in Experiment 2 than in Experiment 1.

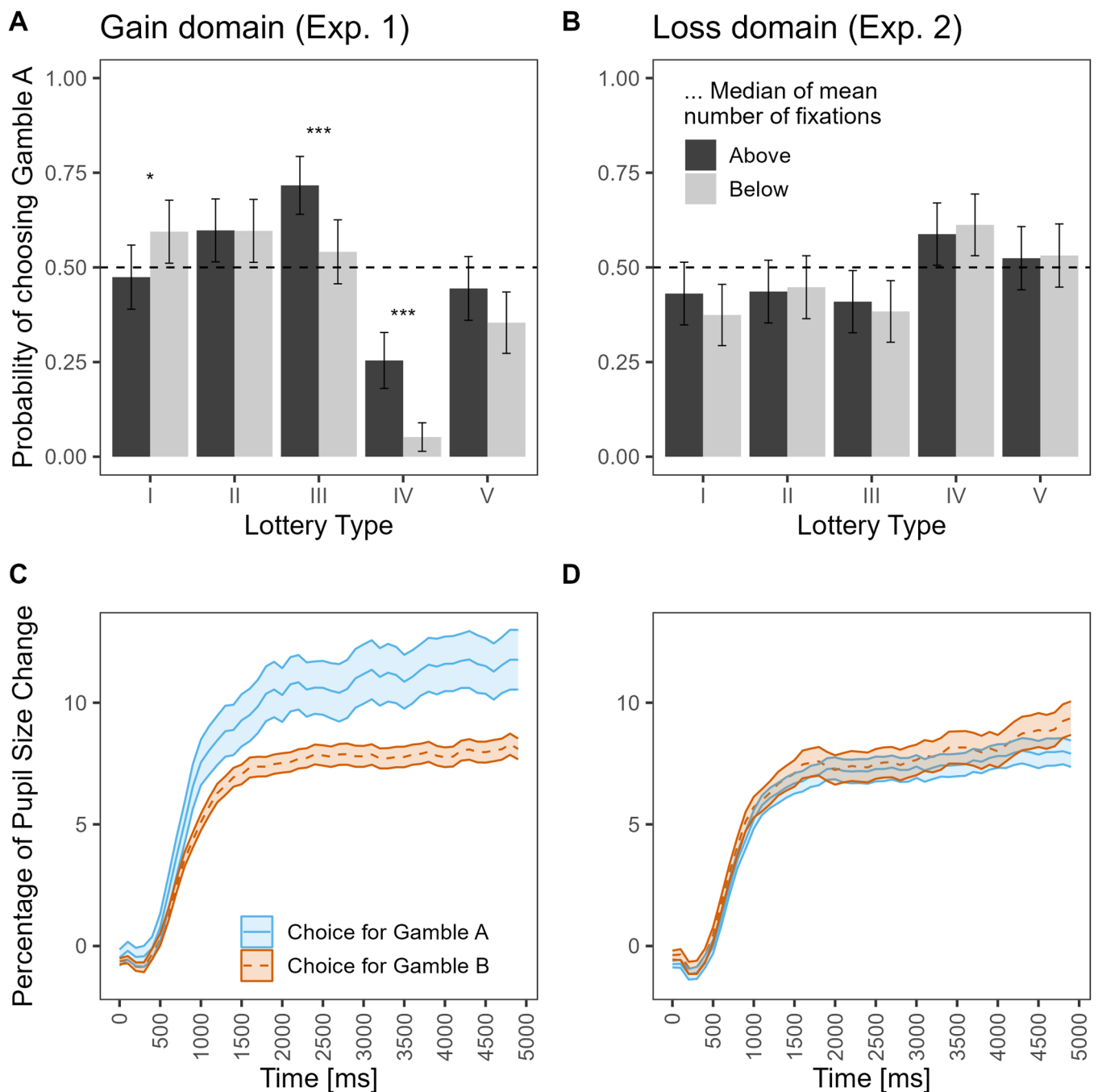


FIGURE 5 | Probability of choosing Gamble A in five lottery types separately for trials with high (above median) or low (below median) number of visual fixations in (A) Experiment 1 (gain domain) and (B) Experiment 2 (loss domain) and percentage of pupil size change over time in Type IV zero-outcome lotteries separately for trials with choice for Gamble A/B in (C) Experiment 1 (gain domain) and (D) Experiment 2 (loss domain). *Note:* The dashed line in Panels A and B marks the 0.50 chance level of choosing Gamble A. Error bars indicate the standard error of the mean. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, for Welch t -test comparing the median split groups (see Table S9 for test statistics). The shaded areas in Panels C and D represent the standard error of the mean. Pupil size changes over time are relative to a pre-stimulus baseline. Type IV had a zero outcome in Gamble A.

Furthermore, Yechiam and Hochman (2013) argued that losses have unique effects on attention. According to their model, increased arousal in response to losses directs attention to the task's outcomes, therefore supporting behavioral consistency and decreases random responses to risk. In line with this view, we found that decision makers, on average, took longer and required more visual fixations to decide on gambles in the loss

domain than it took them to choose between equivalent lotteries in the gain domain (Table 3). This pattern aligned with evidence that losses generate more exploratory search than equivalent gains (Lejarraga and Hertwig 2017).

Surprisingly, we observed more variability in decision times, fixations, and pupil size changes in Experiment 2 than in

Experiment 1. This observation contradicted the argument that losses, relative to gains, should reduce random responses to risk (Yechiam and Hochman 2013). Increased variability could be another reason why differences between lottery types were less clear in Experiment 2 than in Experiment 1.

Our observations aligned with the hypothesis that decision difficulty decreases for lotteries with zero outcomes, especially in the gain domain. This replicated earlier work (Franco-Watkins and Johnson 2011; Glöckner and Herbold 2011; Ludwig, Jaudas, and Achtziger 2020; Schulte-Mecklenbeck et al. 2017). The finding supported the explanation that zero outcomes were essentially ignored in terms of visual attention because they were not worth being seriously considered, as the expected value of these gambles was always zero.

An alternative explanation for the attentional neglect of zero outcomes in the gain domain could be found in research on self-control (e.g., Gross 1998; Hügelschäfer and Achtziger 2017). Decision makers can intentionally avoid zero outcomes to minimize the experienced or anticipated negative affect these outcomes may entail. The intentional avoidance of specific information, and thus, controlled inhibition of automatic attention processes (like directing attention to other information), requires effortful self-control. If zero-outcome avoidance relied on self-regulation, choices should be slower and more cognitively demanding in the presence of zero outcomes. We can rule out this explanation for the gain domain. The results indicated that risky choices were faster and less cognitively demanding if zero outcomes were included in a lottery. When decisions were framed as gains, decision makers avoided the adverse information of zero outcomes. They did so perhaps to keep the psychological impact of these disappointing outcomes low (Galai and Sade 2006; Karlsson, Loewenstein, and Seppi 2009; Zeelenberg 1999). Based on this evidence, we argue that zero-outcome avoidance in the gain domain relied on automatic processes rather than effortful self-control.

There was mixed evidence on the question if the zero effect alone can account for choice patterns usually ascribed to the appeal of certainty (Incekara-Hafalir, Kim, and Stecher 2021). Consistent with a certainty effect in risky choices, gambles with sure gains were chosen more frequently than chance in Experiment 1. However, the choice proportions were not different from the reference category of the lottery task. Our findings thus do not provide strong support for the idea that decision makers are attracted to sure gains (Kahneman and Tversky 1979).

However, our design focused on exploring the zero effect in risky choices and was not attuned to afford a strict test of the certainty-effect hypothesis. Gamble A in sure gain Type II lotteries had two equal outcomes with varying probabilities of winning, for instance, 50 E with a probability of 0.25 and 50 E with a probability of 0.75. We assumed that decision makers would add up the probabilities of the two equal outcomes in one gamble and conclude that this outcome can be achieved with certainty (that the outcome 50 E had a probability of 1). Given that sure gains were presented segregated as two outcomes in one gamble, it is not necessarily the case that participants interpreted the gamble as a sure gain.

Another design aspect that could be viewed as a limitation was that we fully randomized the location of outcomes and probabilities within gambles. We did so to counteract habituation effects that could support heuristic decisions, like searching the decision environment according to a particular strategic sequence. Instead, participants in our studies had to stay focused and actively search information on each trial. However, one could also argue that this design feature rendered the task more difficult, thereby encouraging reliance on other heuristics, like choosing the safe win or avoiding zero outcomes. In fact, fully randomizing the location of gamble attributes appears to result in somewhat slower decisions (cf. table 2 in Ludwig, Jaudas, and Achtziger 2020). We acknowledge this limitation and encourage researchers to systematically test how the presentation format affects decision makers' reliance on simple heuristics, including the zero effect.

In Experiment 1, lotteries with zero outcomes were associated with greater pupil size changes than the more difficult SIM lotteries that did not contain zero outcomes. Hence, pupil size changes over time did not exclusively reflect differences between the lotteries' difficulty (Kahneman and Beatty 1966) and EVmean (Fiedler and Glöckner 2012; Ludwig, Jaudas, and Achtziger 2020) but appeared to also reflect the desirability of outcomes. Overall, pupil size changes were greatest in response to high value gains and lotteries with zero outcomes. Pupil size changes were relatively smaller when lotteries were rather difficult (Type I). To increase our confidence in this finding, we reanalyzed data from Fiedler and Glöckner (2012) available at <https://osf.io/em8h6>. Their Experiment 1 used a lottery choice task like ours, including zero-outcome lotteries and difficult lotteries comparable to our Type I. By modeling pupil size change over the first 15 fixations of each trial, we observed greater changes for zero-outcome lotteries relative to Type I, $b_{zero} = 0.557$ $[-0.062, 1.176]$, but this effect was not significant $\chi^2(2) = 2.92$, $p = 0.088$. As reported by Fiedler and Glöckner (2012), the mean expected value did not affect pupil dilations in this experiment.

The observation that pupil size change was greater for zero outcome lotteries than for other lottery types had three implications. First, it suggested that pupillary responses reflected affective arousal rather than cognitive effort. Type I lotteries were difficult because they required intense information search, as evident in the highest number of fixations per trial and the slowest decisions. Yet, they were associated with relatively smaller pupil size changes than other easier lottery types. Perhaps, Type I lotteries were generally less attractive than the other types because it was challenging to find the best option. Type I lotteries might thus evoke less arousal than other lotteries simply because they are less appealing overall.

Second, the observation that almost sure gains elicited even greater changes in pupil dilation than Type IV–V zero-outcome lotteries (see Figure 4) illustrates that pupillary responses were affected by multiple sources of arousal. The nature of Type III lotteries explained why they would trigger the greatest affective arousal. Because the risk is slightly increased relative to a sure gain in Type II (the probability of an almost sure gain was 0.98 or 0.99), Type III might stimulate gambling behavior and thereby raise arousal in terms of excitement. Both uncertainty (see Urai, Braun, and Donner 2017) and excitement, which should be

accompanied by an increase in state arousal, could be reflected in the pupillary response.

Third, to the extent that pupil size traced arousal, our pupillometric analyses aligned with the view that zero outcomes elicited relatively stronger affective reactions than other outcomes, especially when zero outcomes were included in otherwise gains-oriented decision environments. Higher arousal would not be expected if zero outcomes were ignored merely because value calculations were pointless for these outcomes. We argue that arousal, indicated by greater pupil size changes on zero outcomes, suggested that there may be more to the processing of zero outcomes than just low difficulty. In our view, arousal responses to zero-outcome lotteries signal avoidance motivation (in the gain frame and approach motivation in the loss frame; but note that the evidence was less clear in Experiment 2). Consequently, zero outcomes can guide pre-decisional information search and bias choices.

Differences in EVmean were also reflected in the pupillary response (Fiedler and Glöckner 2012), but only in Experiment 1. Although the average EVmeans of the five lottery type categories were very similar for three types in Experiment 1 (on average, roughly 35E in Types III and V), the remaining lottery types had considerably larger average EVmean (around 50E in Types I and II). It was surprising that the latter two lottery types generated the smallest changes in pupil dilation in our experiment, given the prior observation that pupils dilated as a function of EVmean (Fiedler and Glöckner 2012). The issue was fixed in Experiment 2. All lottery type categories had a comparable average EVmean. EVmean did not predict pupil size changes in Experiment 2. But more importantly, we still observed differences in pupil size change based on lottery types, although less clearly than in Experiment 1. This observation strengthened our conclusion that affective responses to salient gamble attributes were reflected in pupillary responses. Importantly, we ruled out that pupil size differences between the lottery types observed in Experiment 1 were solely due to desirability differences, as captured by EVmeans.

Moreover, our studies show connections to two streams of the literature that are worthy of a brief discussion here: research in decision theory focusing on integrating attention as a key component of formal models of risky choice (e.g., Glickman et al. 2019; Krajbich, Armel, and Rangel 2010; Smith and Krajbich 2019) and investigations into the “zero-price effect” in consumer behavior (Mazar, Shampanier, and Ariely 2017; Palmeira 2011).

First, as discussed above, research on decisions under risk has relied increasingly on eye movement data to provide deeper insight into the decision process and inform theory development (e.g., Glöckner and Herbold 2011; Krajbich, Armel, and Rangel 2010; Stewart, Hermens, and Matthews 2016). Several studies have advanced formal choice models that incorporate attention as a key component of the decision process (Glickman et al. 2019; Smith and Krajbich 2018, 2019). For instance, the attentional drift diffusion model (aDDM; Krajbich, Armel, and Rangel 2010) describes decision processes as noisy diffusion processes of evidence accumulation and suggests that visual fixations modulate the process of value integration, such that

evidence accumulation is biased in favor of the information that is being fixated at any point in time during the decision-making process. In other words, the model predicts that the less a choice alternative is looked at, the less likely it is to be chosen. This prediction (as many others that follow from the aDDM) has received robust support in several studies and across different decision-making domains (see, e.g., Smith and Krajbich 2018, 2019).

Our results are generally in line with the model. However, there are some observations that might seem puzzling. For example, in Experiment 2, we observed that over the course of making their decisions, participants attended progressively less to A2 outcomes. On a side note, this observation contrasts with Stewart et al.'s (2016, 128) conclusion that “across choices, people make the same sorts of eye movements [...] and they just make more of the same type of eye movements for harder choices” in Type III, IV, and V lotteries (see Figure S1). A2 outcomes were zero outcomes in Types IV, V, and outcomes tied to very small probabilities (0.01 or 0.02) in Type III. Based on the aDDM, one might expect that decision makers would choose Gamble A less frequently in these lotteries, given that they direct their attention away from A2 outcomes. However, choice proportions for Gamble A were indifferent from the 0.5 chance level in Type V and even significantly greater than chance in Type IV (see Figure 2 and Table S3). They were significantly below chance only for choices in Type III lotteries. Although a comprehensive test of predictions derived from the aDDM and related models (e.g., Glickman et al. 2019) was outside the scope of our study, we encourage future research to further explore the boundary conditions under which the qualitative predictions of these process models hold, particularly in under-researched special cases like zero outcomes in the loss domain.

Second, consumer behavior research demonstrated that many people overreacted to a zero dollar price tag. For example, Shampanier, Mazar, and Ariely (2007) asked consumers in fictive and real shopping situations to choose between two pieces of chocolate candy. They were interested in how consumers would behave when the prices of both candies were reduced by the same amount of money so that one item was effectively offered for free. As might be expected for a free product, the demand for the free chocolate increased. But more interestingly, the perceived benefit of the candy that was now for free also increased, beyond what would be expected based on the reduced price. It appeared that free products were not only assessed in terms of their zero cost of purchase but that zero prices also added to the perceived benefit of the product in question. Brain-imaging research suggested that affective responses caused this zero-price effect (Votinov et al. 2016). In addition, the bias was not confined to binary food choices (Mazar, Shampanier, and Ariely 2017; Nicolau and Sellers 2012; Palmeira 2011). For instance, Nicolau and Sellers (2012) found that the demand for a specific hotel grew when a free breakfast was included, whereas the demand for an alternative hotel that was initially preferred over the former declined simultaneously. Unsurprisingly, zero-cost opportunities are very appealing to consumers.

Like this earlier work on the zero-price effect, we concluded that zero outcomes in risky choices triggered overreactions to the value zero. Zero outcomes were ironically interpreted like

gains in the loss domain, just like consumer products were evaluated more favorably when the price dropped to zero. Taken together, our results suggest that processing zero outcomes was immediate, quick, and effortless and did not require conscious intent (Chen and Bargh 1999; W. Schneider and Shiffrin 1977). Consistent with a prominent role of affect in economic decisions (Bateman et al. 2007; Finucane et al. 2000; Payne, Laughhunn, and Crum 1980), our findings align with the idea that zero outcomes distinctly relate to affective and motivational processes, contingent on the decision environment. Data from our two experiments suggest that zero outcomes in the gain domain, presumably perceived subjectively as potential losses, can elicit strong motivational forces that can subsequently bias information search and choice behavior in decisions under risk.

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Data Availability Statement

The data that support the findings of this study are openly available in OSF at <https://osf.io/rzd8c>, reference number rzd8c.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.